PRISM PRIME

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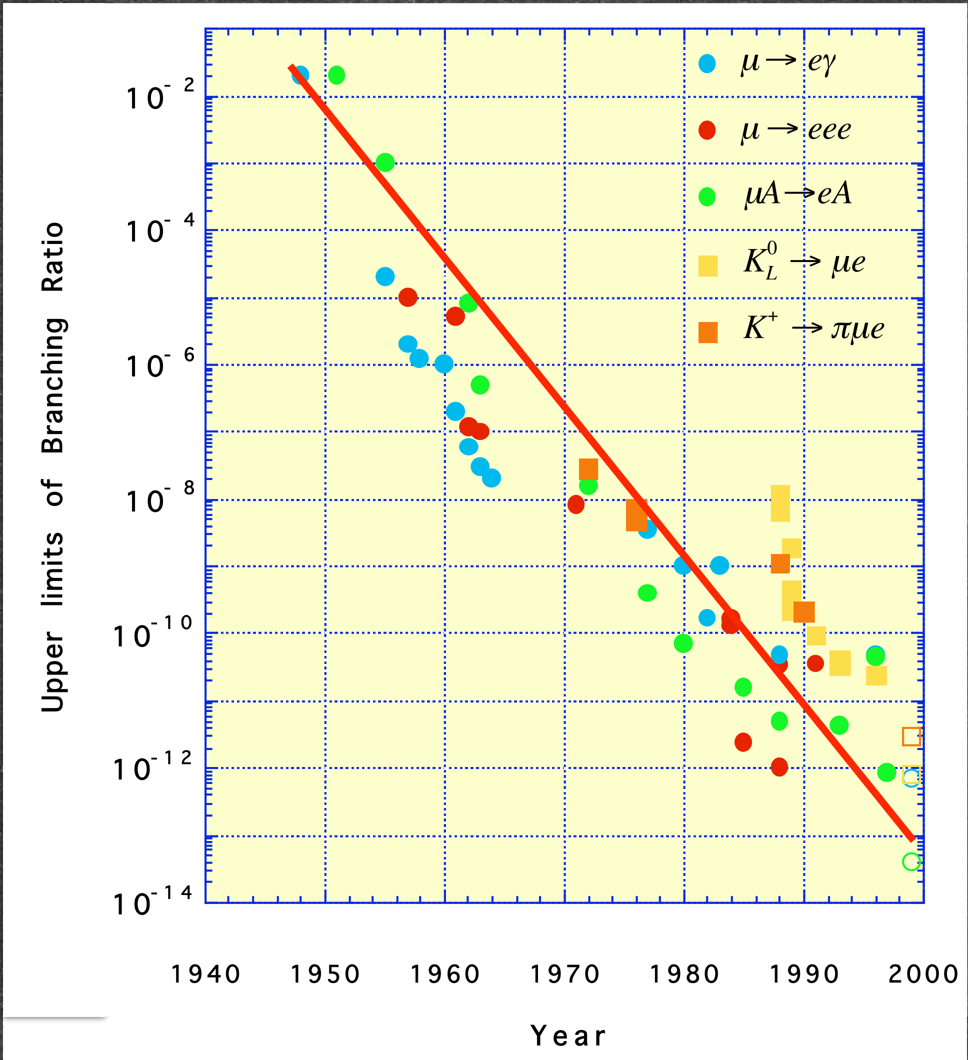
BNL mu-e workshop

Outline

- Physics : Charged Lepton Flavor Violation
- Phenomenology : Charged Lepton Flavor Violation
- PRISM / PRIME
- PRISM FFAG ring R&D
- PRISM Roadmap
- Summary

Physics:
Lepton Flavor Violation

History of LFV Searches



Lepton Flavor Violation (LFV)

No (charged) LFV in the Standard Model

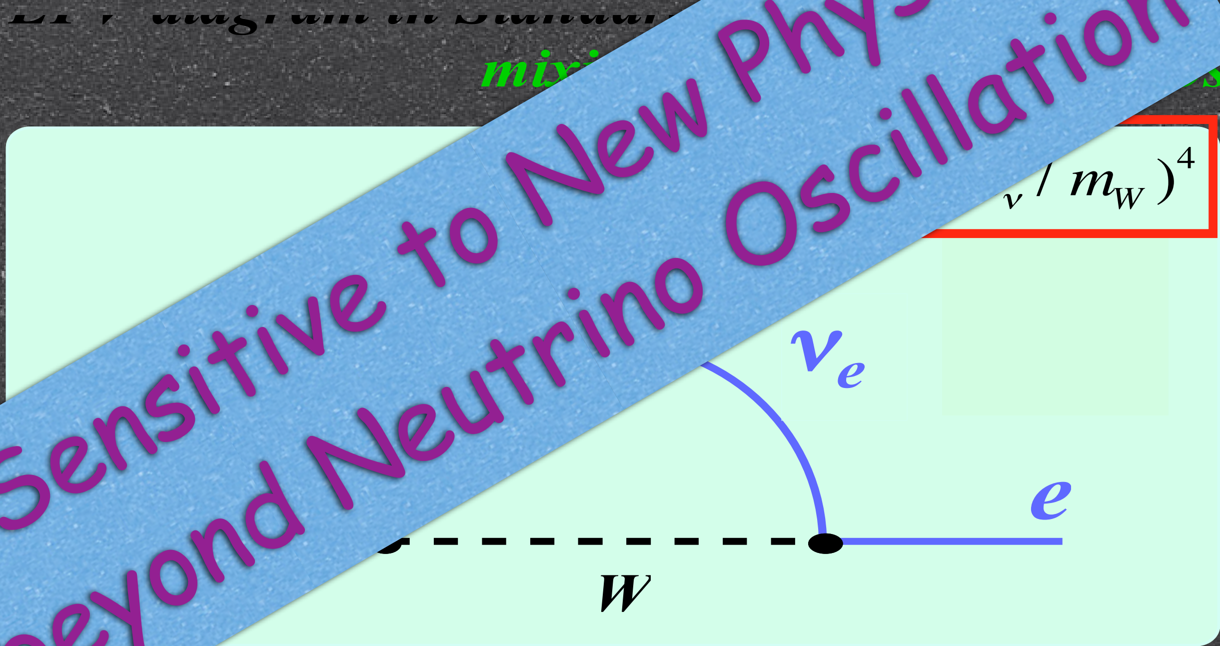
Upper limits improved by two orders of magnitude per decade.

Any good reasons to continue LFV searches further ?

Yes !

Neutrino Mixing for LFV

- Observed neutrino oscillation (mixing) implies lepton flavor violation in the neutrin... ...or. How does it contribute to char...



Sensitive to New Physics beyond Neutrino Oscillation

Very Small (10^{-50})

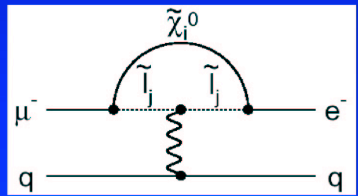
LFV Models beyond SM

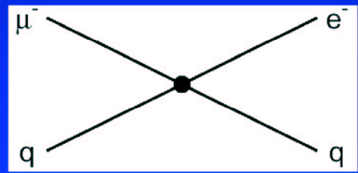
Sensitivity to Different Muon Conversion Mechanisms

MECO

Supersymmetry

Predictions at 10^{-15}





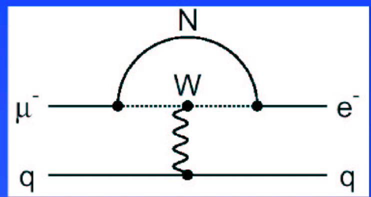
Compositeness

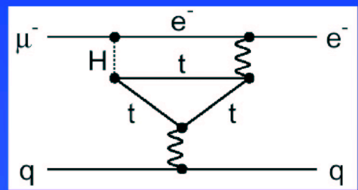
$\Lambda_c = 3000$ TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 =$

8×10^{-13}





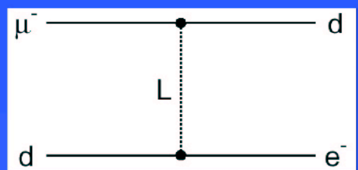
Second Higgs doublet

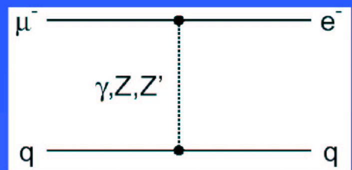
$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$

Leptoquarks

$M_L =$

$3000\ (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2





After W. Marciano

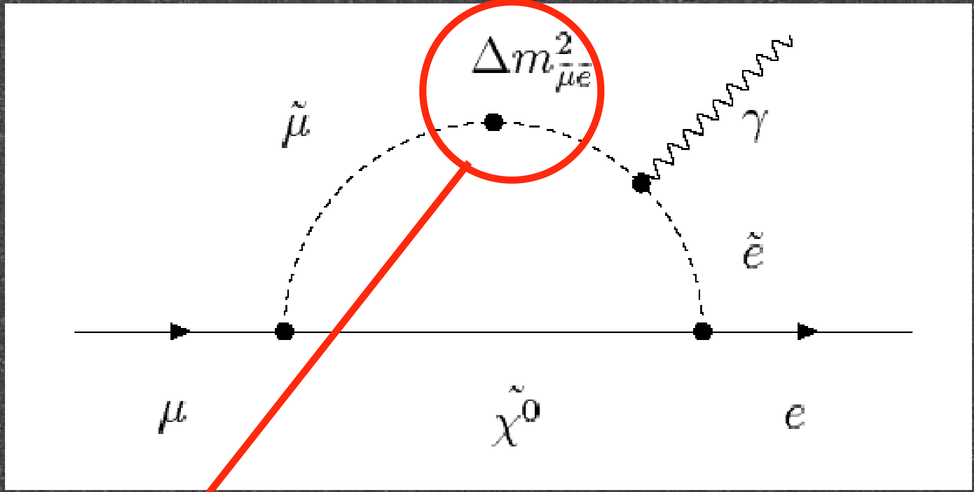
Heavy Z', Anomalous Z coupling

$M_{Z'} = 3000$ TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

SUSY for LFV

$$\mu^+ \to e^+\gamma$$



$$m^2_{\tilde{l}} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$

In SUSY, LFV processes are induced by the off-diagonal terms in the slepton mass matrix. In MSSM, no off-diagonal terms exist @Planck, and need more.

How ?

How Sleptons Mixed ?

$$(m^2_{\tilde{l}})_{ij} = m_0^2 \delta_{ij}$$

@ M_planck

SUSY-GUT

GUT Yukawa interaction

SUSY Seesaw Model

Neutrino Yukawa interaction

$$(\Delta m^2_{\tilde{l}})_{ij} \neq 0$$

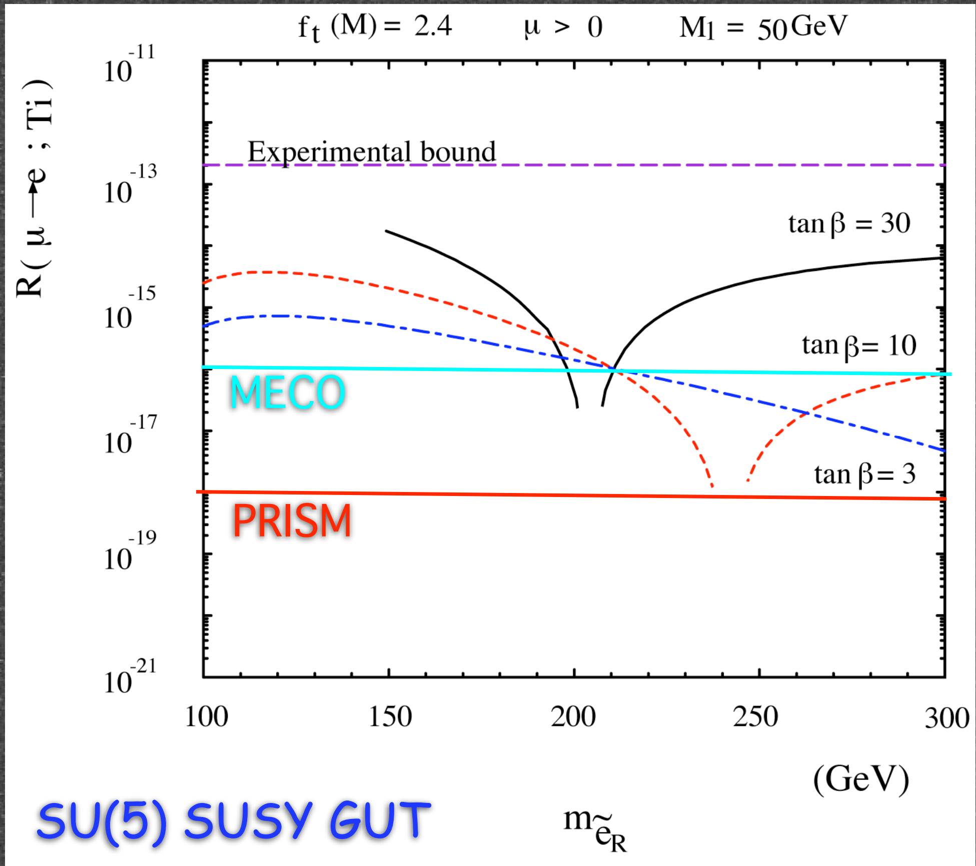
$$(m^2_{\tilde{L}})_{21} \sim \frac{3m_0^2 + A_0^2}{8\pi^2} h_t^2 V_{td} V_{ts} \ln \frac{M_{GUT}}{M_{R_s}}$$

CKM matrix

$$(m^2_{L})_{21} \quad \frac{3m_0^2 + A_0^2}{8\pi^2} h_i^2 U_{i1} U_{i2} \ln \frac{M_{GUT}}{M_{R_S}}$$

Neutrino oscillation

SUSY-GUT



right-handed slepton mass

Slepton mixing is induced through radiative correction from GUT (where quarks and leptons are in the same multiplet) to weak scale.

- SUSY SU(5) predictions

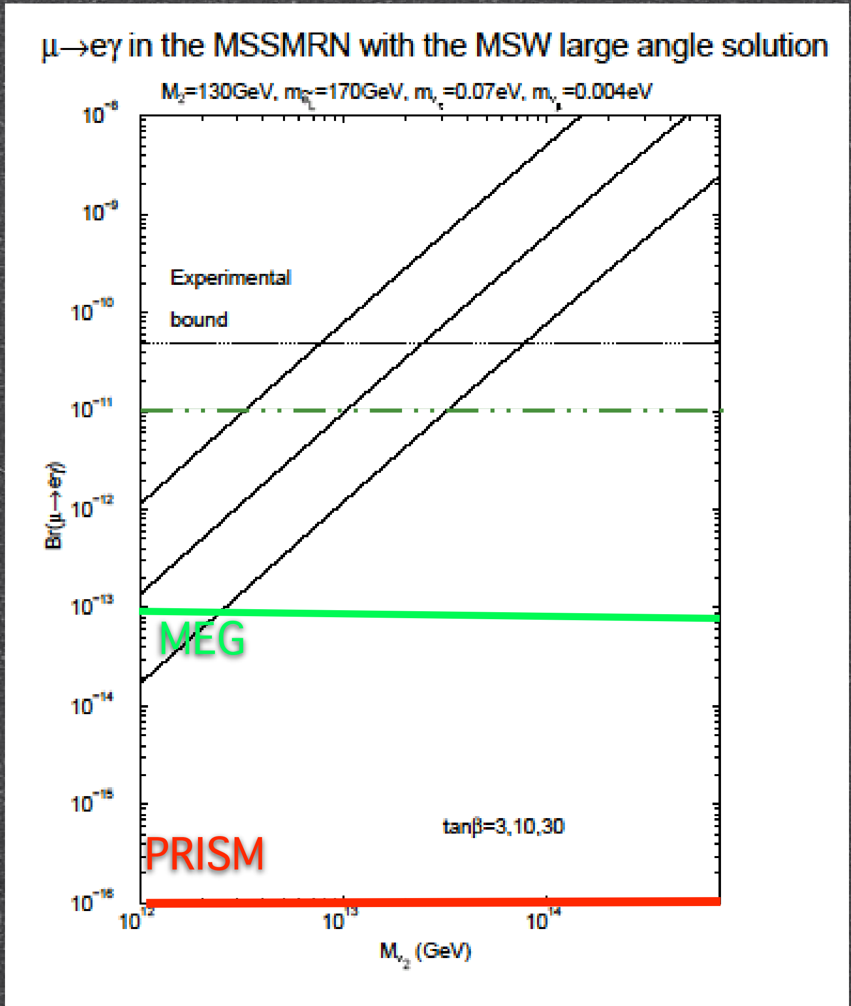
  BR $(\mu \to e\gamma) \approx 10^{-14} \div 10^{-13}$

- SUSY SO(10) predictions

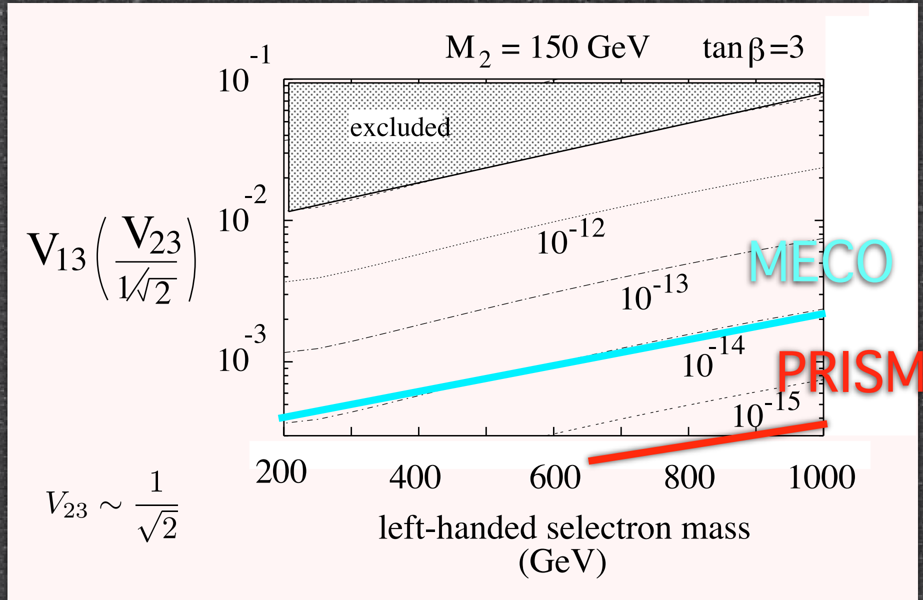
  $BR_{SO(10)} \approx 100\ BR_{SU(5)}$

Predictions are just a few orders of magnitude smaller than the present limit. Future experiments might cover.

SUSY Seesaw Model



right-handed neutrino mass



Through SUSY, only way to access heavy right-handed neutrinos in seesaw models.

LHC, SUSY and LFV

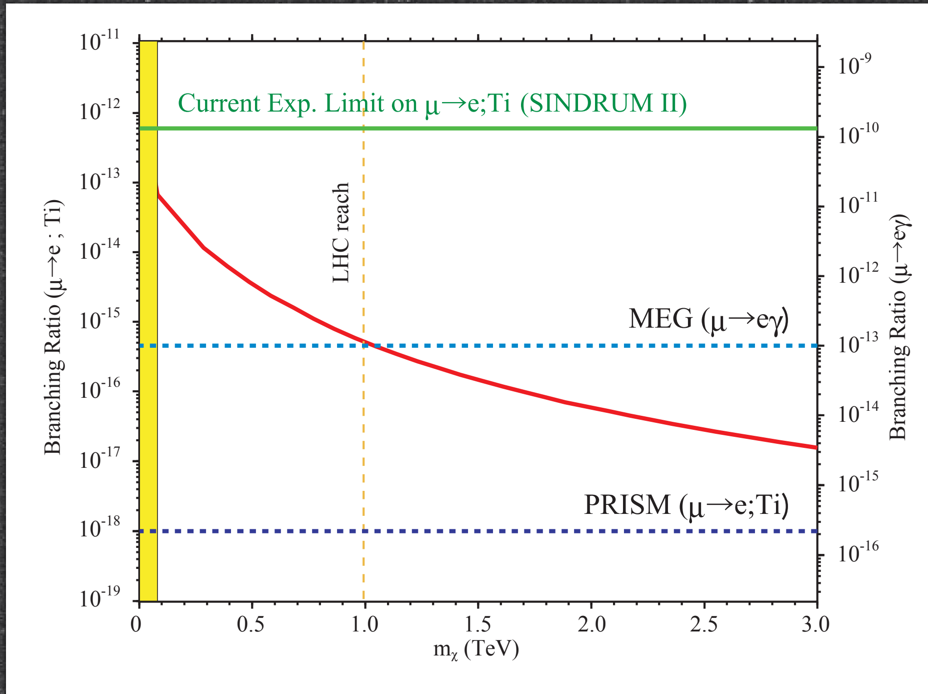
If LHC finds SUSY

LFV search would become more important, since the slepton mixing matrix should be studied.
- SUSY-GUT
- SUSY Seesaw models.

If LHC not find SUSY

LFV search would become more important, since

from A.Masiero et al.



Why the Muon ?

- LFV Sensitivity in the muon will be the highest over the other systems because of enormous beam intensity (~10^{12}/sec) thanks to R&D studies of neutrino factory front-end.
- The muon provides a clean test ground, on the contrast to hadrons where QCD corrections needed introduces sensitivity limits,

LFV Catalog

For the muons,

ΔL=1

- $\mu^+ \to e^+\gamma$
- $\mu^+ \to e^+e^+e^-$
- $\mu^- + N(A,Z) \to e^- + N(A,Z)$

SUSY

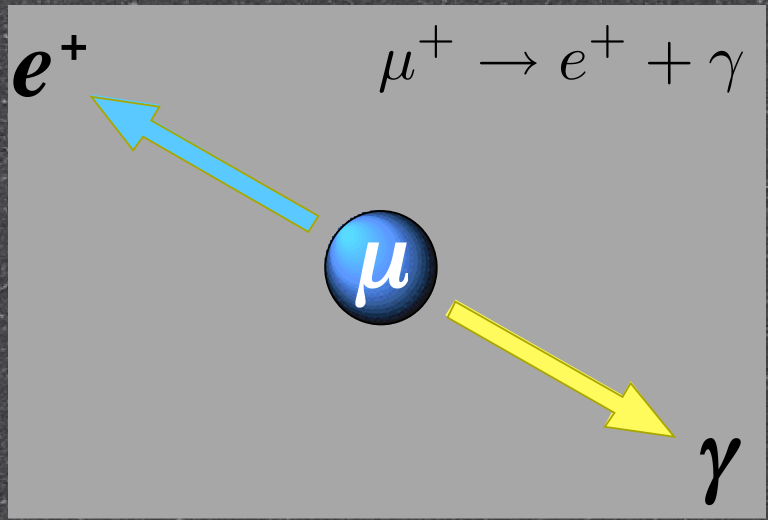
- $\mu^- + N(A,Z) \to e^+ + N(A,Z-2)$

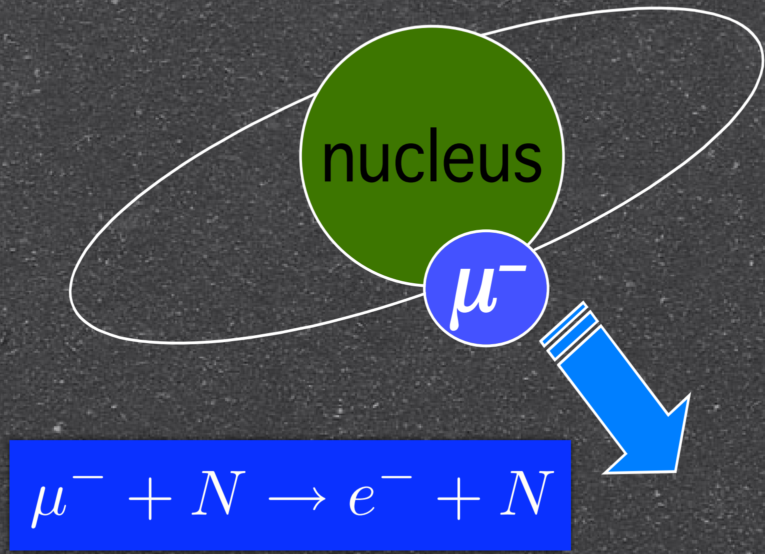
Majorana nature

ΔL=2

- $\mu^+e^- \to \mu^-e^+$
- $\mu^- + N(A,Z) \to \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \to \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \to \mu^+\mu^+\mu^- + N(A,Z-1)$

μ→eγ & μ-e conversion





Signature

$$E_e = E_\gamma = m_\mu/2$$

back-to-back, same time

Background

(1) radiative decay

(2) accidentals

Signature: $E_e = m_\mu - B_\mu$

monoenergetic electron

Background:

(1) bound muon decay

(2) radiative pion/muon catpure

(3) cosmic rays, etc.

Photon-mediated SUSY LFV

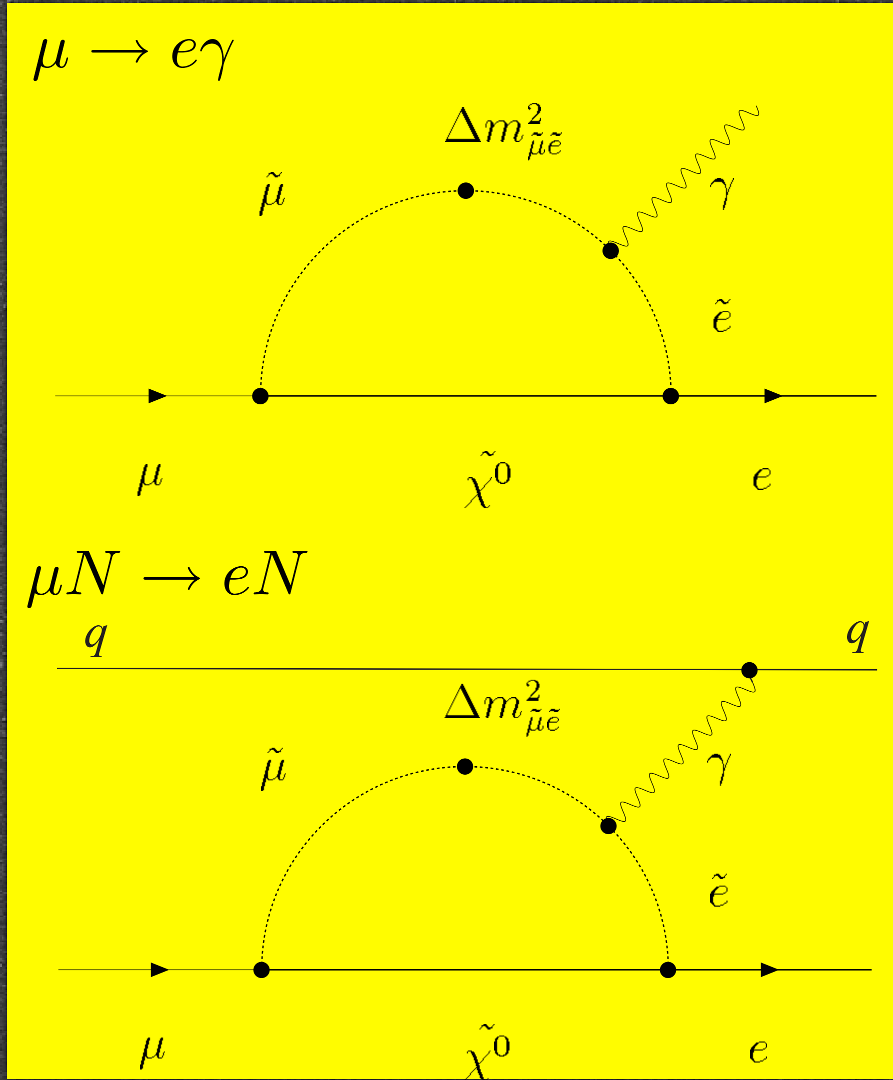
$\mu - e$ conversion vs.
$\mu \to e\gamma$

If photon-mediated,

$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{100}$$

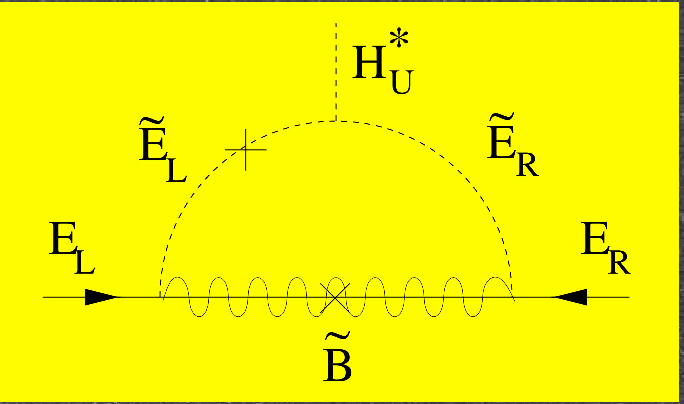
But, experimentally,

$\mu \to e\gamma$	$< 1.2 \times 10^{-11}$
$\mu N \to eN$	$< 6 \times 10^{-13}$



Higgs-mediated SUSY LFV

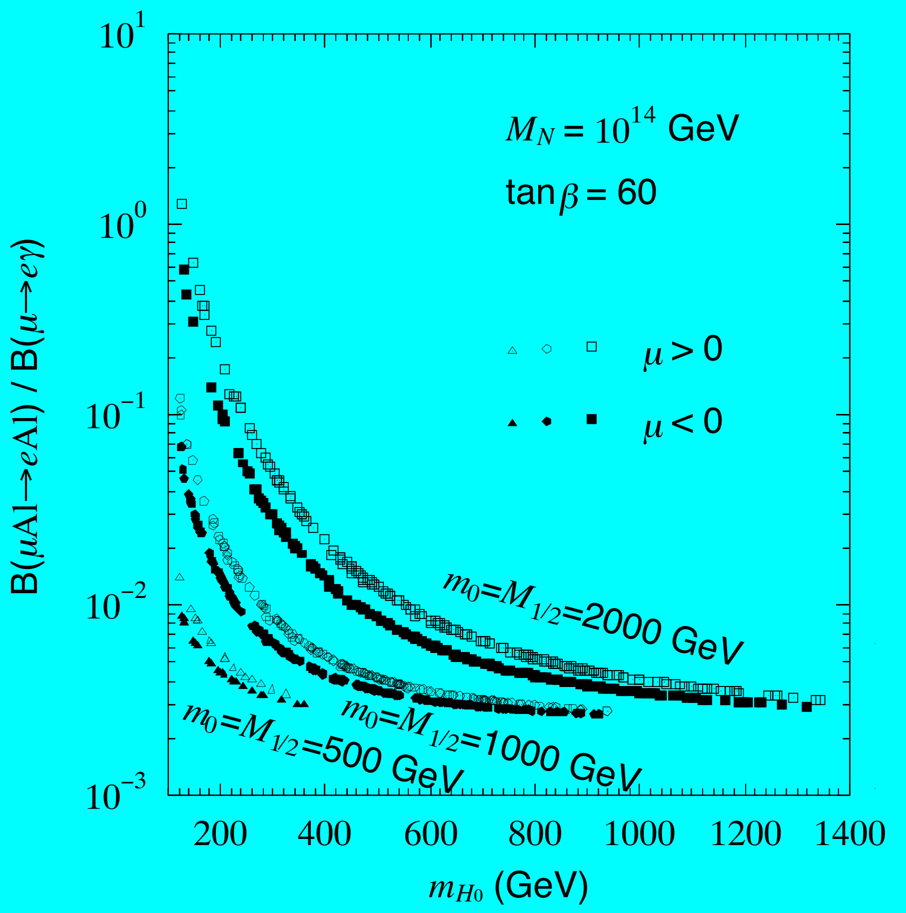
Higgs-exchange for LFV in SUSY Seesaw model



As the H_0 mass is light, the contribution of the Higgs-mediated diagram becomes larger.

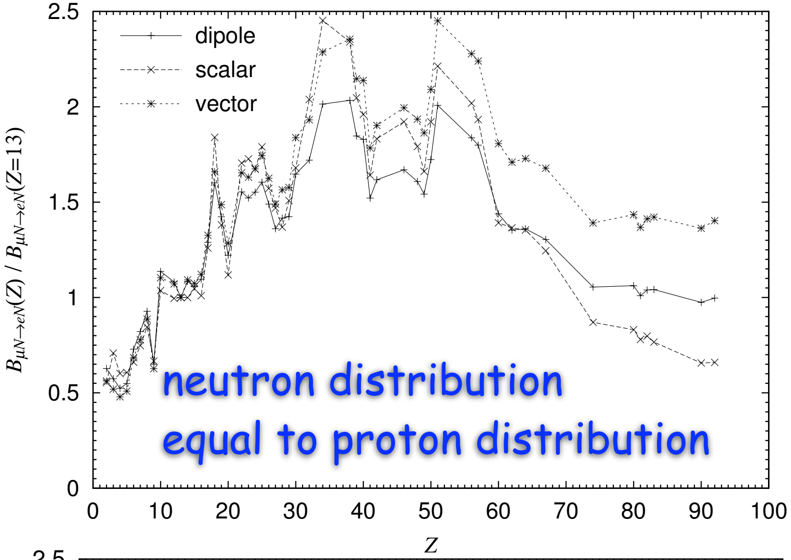
$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim O(1)$$

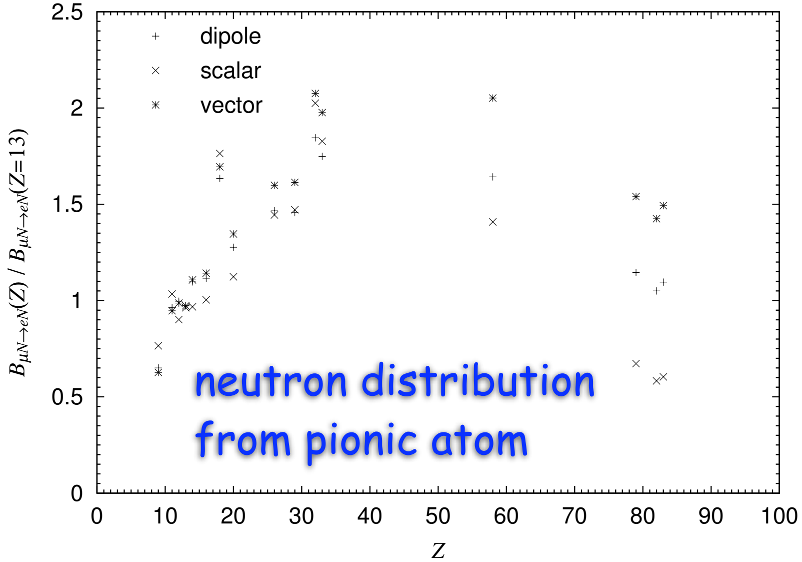
at $H_0 \sim 200$ GeV

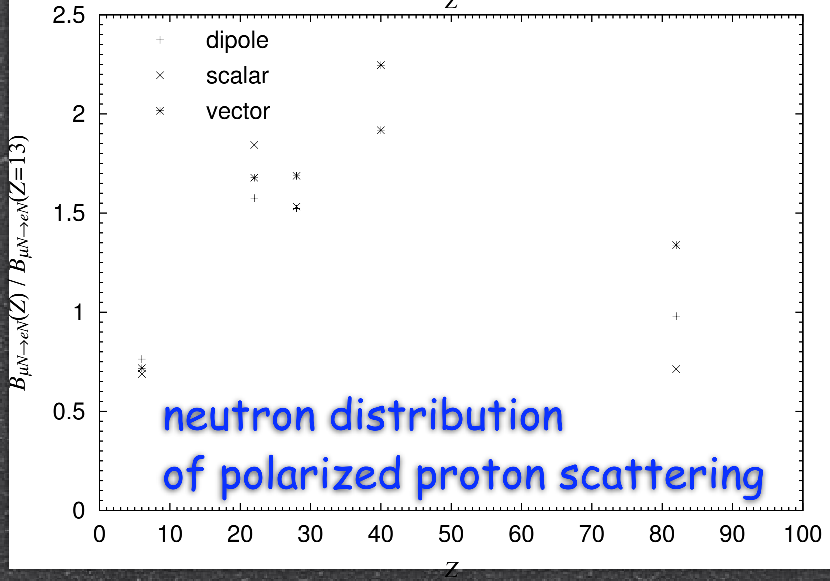


Kitano, Koike, Komine, Okada

Z dependence







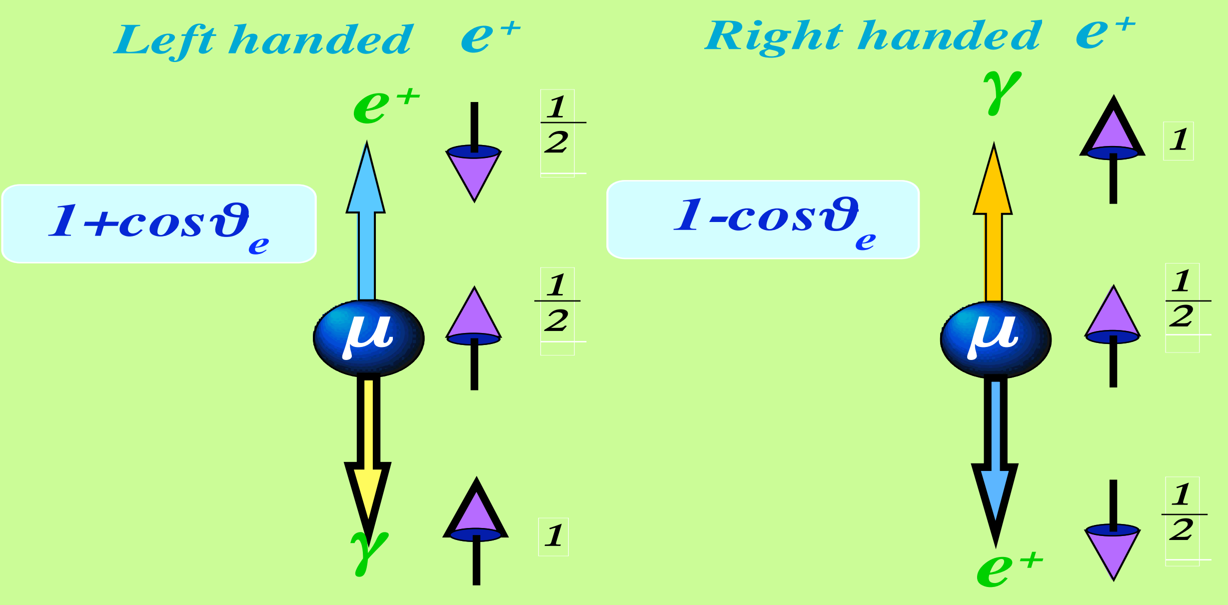
normalized at Al target.

For heavy target, difference of the interactions might be seen ?

R. Kitano, M. Koike, and Y. Okada, 2002

after observation

Polarized $\mu \to e\gamma$

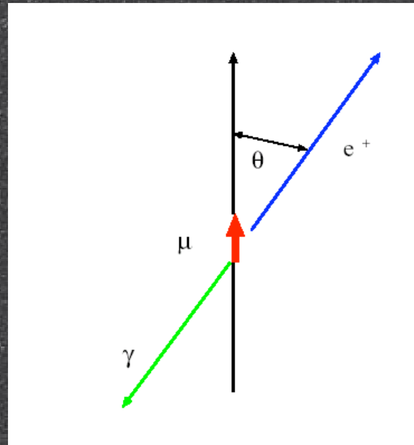


useful to distinguish different theoretical models

SU(5) SUSY-GUT	non-unified SUSY with heavy neutrino Left-right symmetric model

SO(10) SUSY-GUT

Y.Kuno and Y. Okada, Physical Review Letters 77 (1996) 434
Y.Kuno, A. Maki and Y. Okada, Physical Reviews D55 (1997) R2517-2520

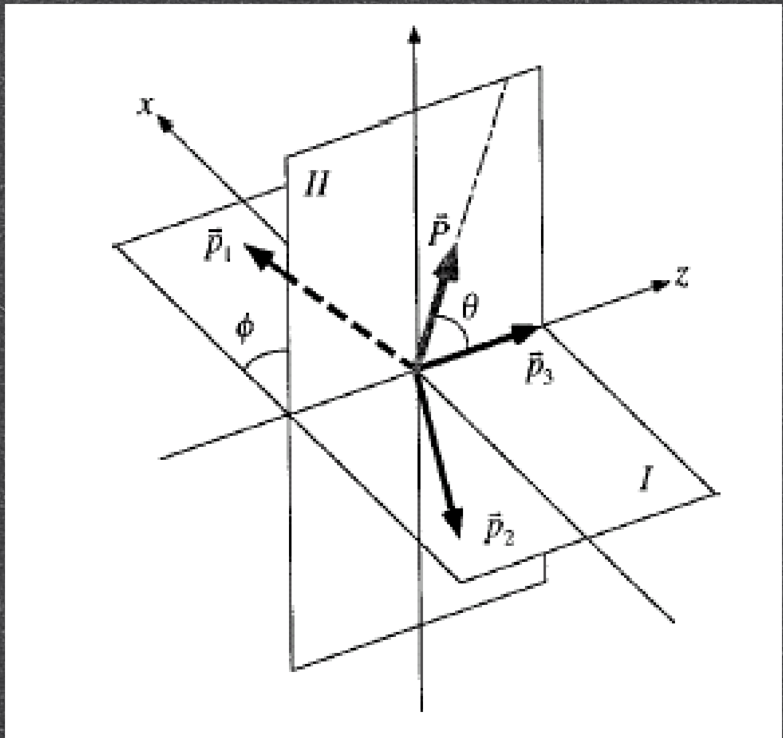


P-odd asymmetry reflects whether right or left-handed slepton have flavor mixing,

after observation

T-odd (CPV) in LFV

$$\mu^+ \to e^+ e^+ e^-$$



Two P-odd and one T-odd asymmetry

$$\vec{P}_\mu \cdot (\vec{p}_{e^+} \times \vec{p}_{e^-})$$

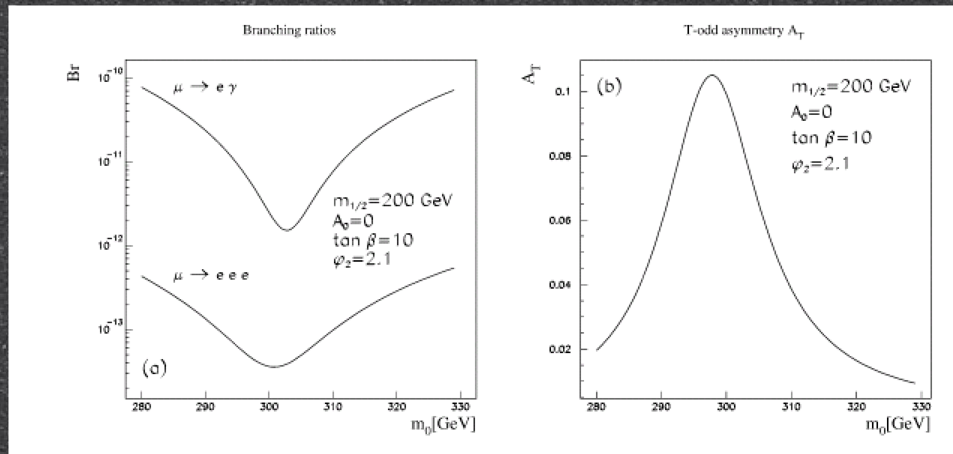
P and T-odd asymmetries in SUSY GUT models

	SU (5)	SO (10)
$A_{\mu\to e\gamma}$	$+100\%$	-100% − +100%
A_{P_1}	-30% − +40 %	$\simeq -A_{\mu\to e\gamma}/10$
A_{P_2}	-20% − +20 %	$\simeq -A_{\mu\to e\gamma}/6$
$\lvert A_T \rvert$	$\lesssim 15\%$	$\lesssim 0.01\%$

Y.Okada, K.Okumura and Y.Shimizu, 2000

Y.Okada,K.Okumura,and Y.Shimizu, 2000

T-odd asymmetry in the SUSY seesaw model



Leptogenesis

J.Ellis,J.Hisano,S.Lola, and M.Raidal, 2001

LFV Phenomenology

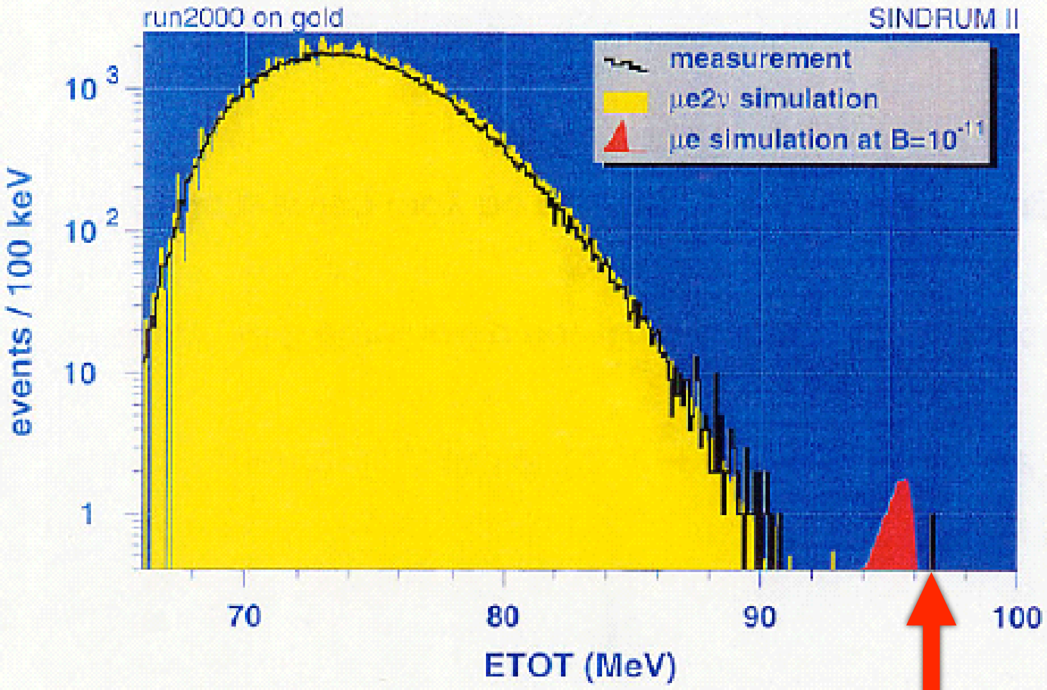
Upper Limits for LFV

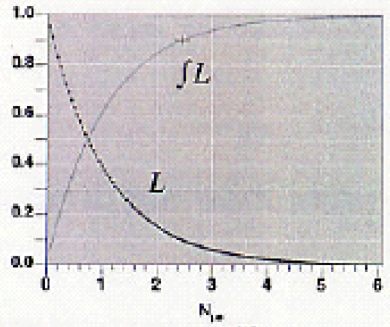
Process	Current	Future
$\mu^+ \to e^+\gamma$	1.2×10^{-11}	<10^{-13}(MEG)
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	
$\mu^- A \to e^- A$ (Ti)	6.1×10^{-13}	<10^{-18}(PRISM)
$\mu^- A \to e^- A$ (Al)		<10^{-16}(MECO)
$\tau \to \mu\gamma$	3.2×10^{-7}	
$\tau \to lll$	$1.4 - 3.1 \times 10^{-7}$	
$G_{Mu\overline{Mu}}/G_F$	3×10^{-3}	$\Delta L_f = 2$

SINDRUM-II μ-e conversion

Final result

μe Conversion on Gold





$\mathcal{L}(N_{\mu e})$ and $\int_0^{N_{\mu e}^{max}} \mathcal{L}(n)dn.$

μ^- stops	$4.4 \pm 0.3 \ \times 10^{13}$
$f_{cap} \times \Omega \times \epsilon_{tot}$	7.0%
single event sensitivity	$3.3 \pm 0.2 \ \times 10^{-13}$
90% C.L. limit	2.45 events

In the likelihood analysis of the energy distribution a flat background from cosmic rays and radiative pion capture was allowed.

Result: $B_{\mu e}^{gold} < 8 \times 10^{-13}$ 90% C.L.

Which Muon LFV Process Next ?

	issue	beam requirement
$\mu \longrightarrow e\gamma$	detector-limited	a continuos beam
$\mu \longrightarrow eee$	detector-limited	a continuos beam
$\mu N \longrightarrow eN$	beam-limited	a pulsed beam

Beam Requirements for μ-e conversion

Beam is critical element for μ-e conversion

MECO

- Higher muon intensity
  - more than 10^{12} μ^-/sec
- pulsed beam
  - rejection of background from proton beam

- Less beam contamination
  - no pion contamination
    - ⇛ long flight path
  - beam extinction between pulses
    - ⇛ kicker magnet

- Narrow energy spread
  - allow a thinner muon-stopping target
    - ⇛ better e^- resolution and acceptance

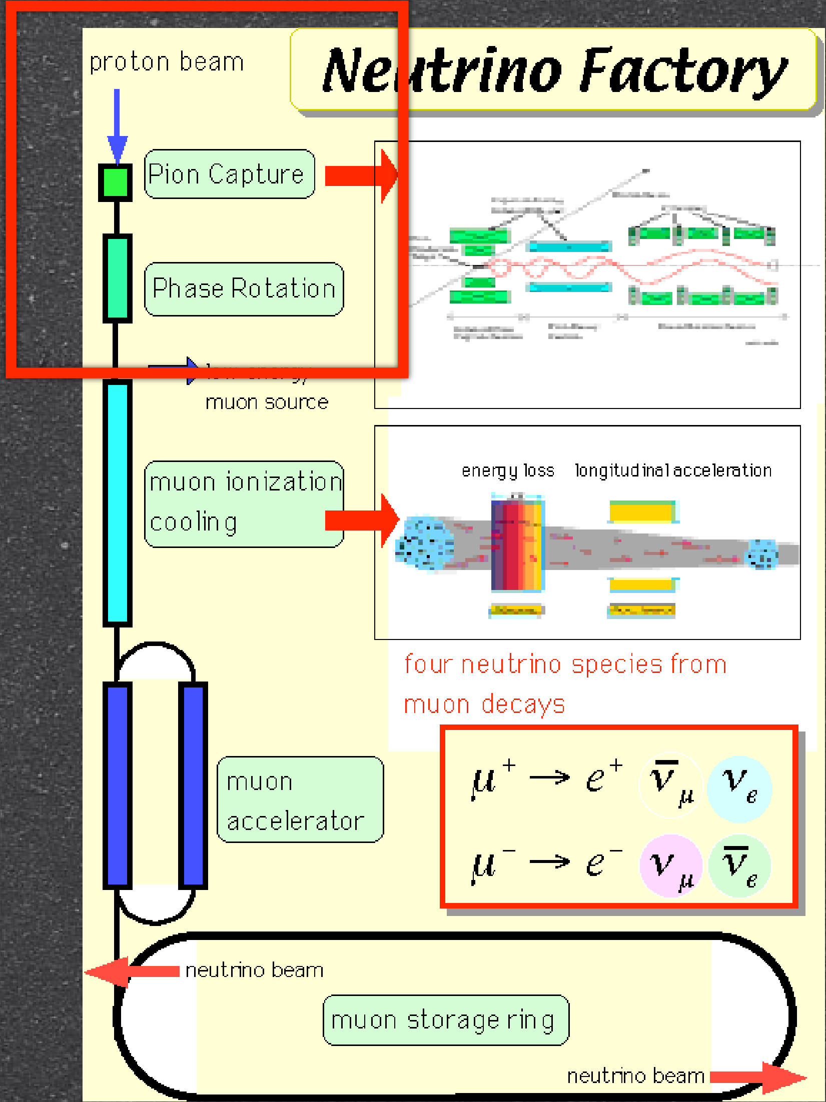
- Point Source
  - allow a beam blocker behind the target
    - ⇛ isolate the target and detector
    - ⇛ tracking close to a beam axis

PRISM

PRISM

Front End of NuFACT

- Neutrino Factory (NuFACT) aimed to produce about 10^{14} muons/sec.
- The front-end of NuFACT would provide a muon beam of high intense and high luminosity.

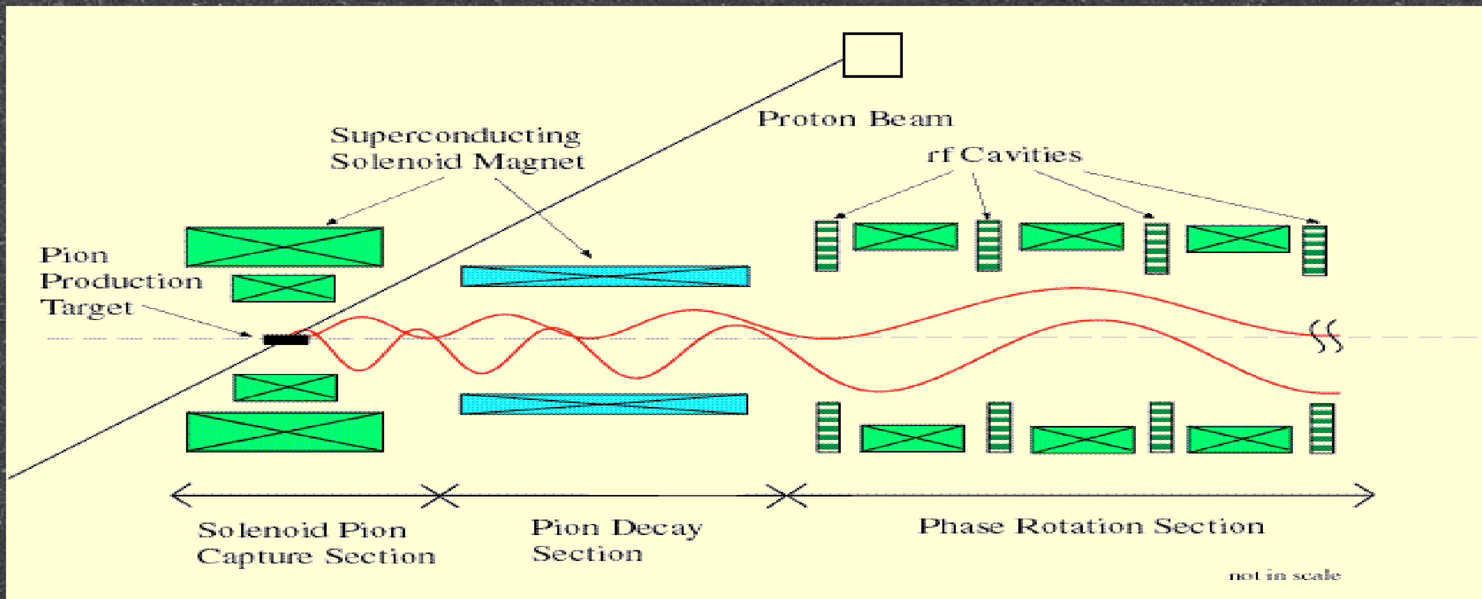


PRISM

PRISM=Phase Rotated Intense Slow Muon source

PRISM is a high intensity muon source with narrow energy spread and high purity.

- high intensity: (Solenoid Pion Capture)
- narrow momentum width: (Phase rotation)
- small emittance (in future): (Cooling)



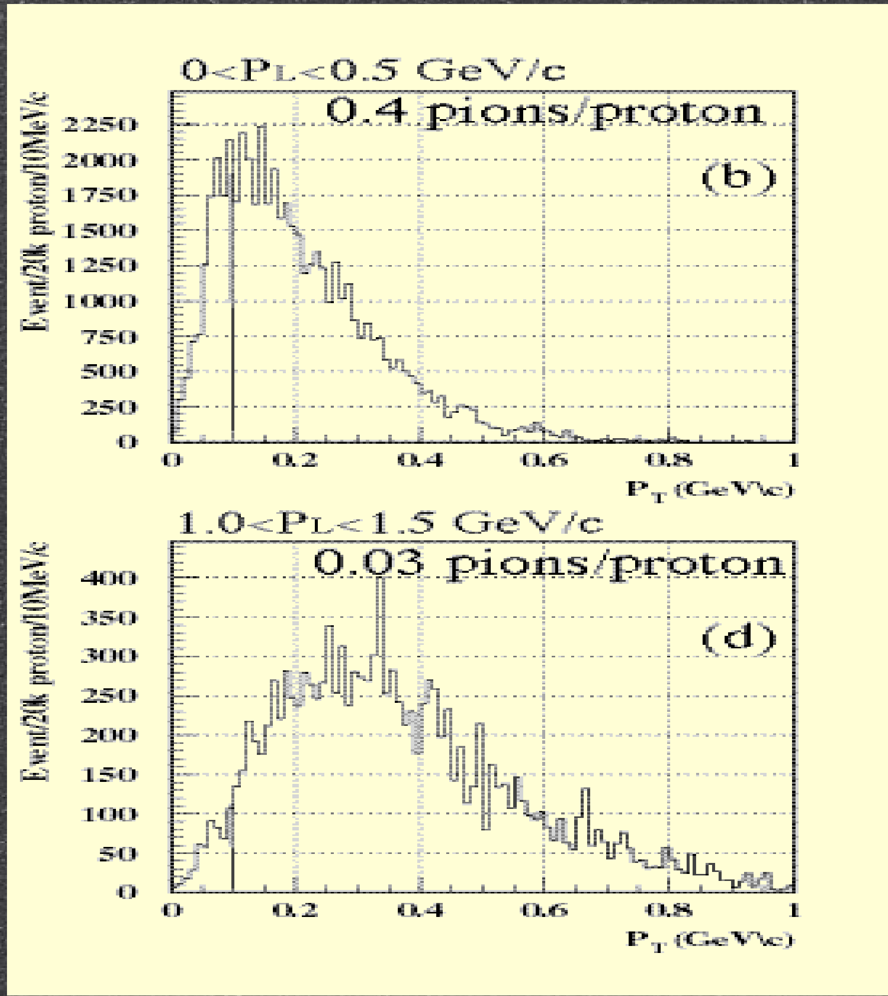
Solenoid Pion Capture

- maximum transverse momentum

$$P_T(MeV/c) = 0.3 \times H(kG) \times \left(\frac{R}{2}\right)(cm)$$

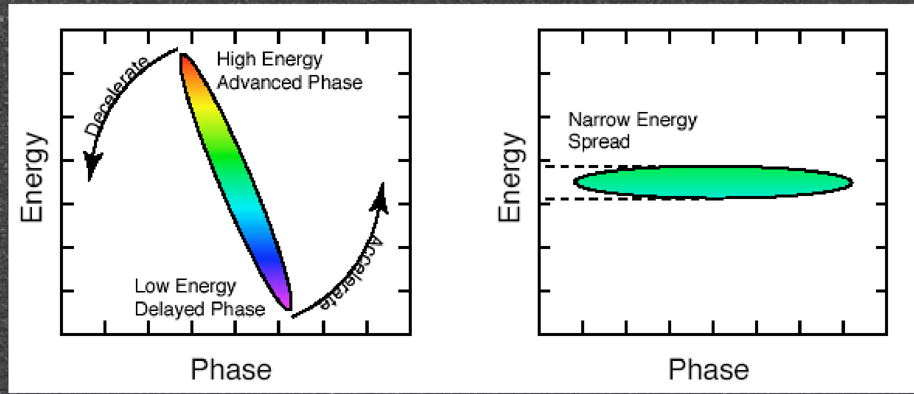
  - *R* : radius of magnet
  - *ex: H*=120kG(=12T), *R*=5cm
    - P_T < 90 *MeV/c*
- capture yields

about 0.4 pions/proton for 0.75MW

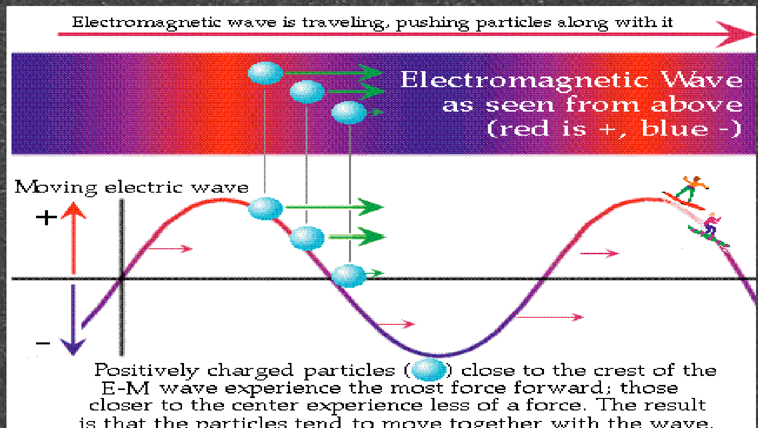


What is Phase Rotation ?

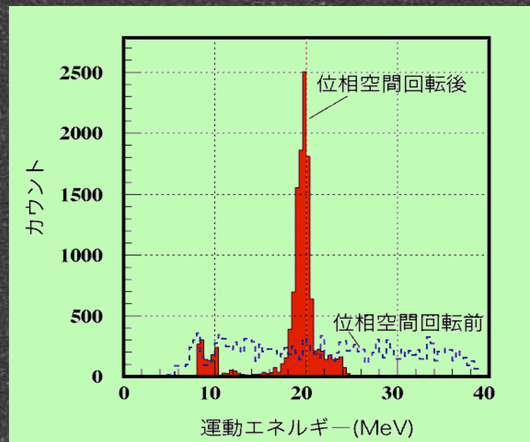
Phase rotation = decelerate particles with high energy and accelerate particle with low energy by high-field RF so as to make the energy spread narrower.



If proton bunch is narrow, high-energy particles come earlier and low-energy particles come late.



Need Compressed Proton Bunches



FFAG for Phase Rotation

- a ring instead of linear systems
  - reduction of # of rf cavities
  - reduction of rf power consumption
  - compact

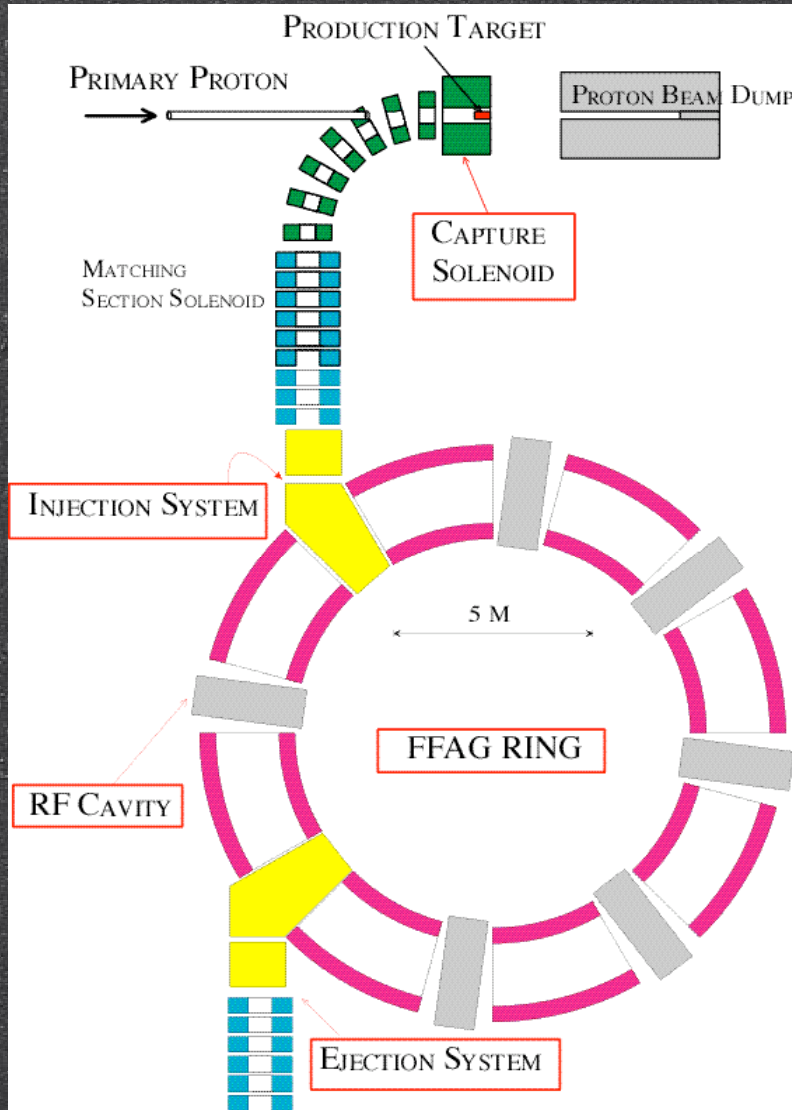
FFAG = Fixed Field Alternating Gradient Synchrotron

- synchrotron oscillation for phase rotation
  - not cyclotron (isochronous)
- large momentum acceptance
  - larger than synchrotron
  - ± several 10 % is aimed
- large transverse acceptance
  - strong focusing
  - large horizontal emittance
  - reasonable vertical emittance at low energy

PRISM

PRISM=Phase Rotated Intense Slow Muon source

- muon intensity: 10^{11}~10^{12} /sec
- central momentum: 68 MeV/c
- narrow momentum width:
  - 3 % (<--- 30 %)
  - by phase rotation (5-6 turns)
- pion contamination : 10^{-18} for 150m
- Repetition : 100 Hz



Important Backgrounds

- Pions in a beam (radiative pion capture)
  - reduction of pions in a beam by a long flight length of the beam line
- Electrons from muon decay in orbit
  - improvement of resolution of electron detection
    - narrow beam energy width
- Cosmic ray
  - reduction of a duty factor of measurement

PRIME

PRIME

PRIME = PRIsm Mu E experiment

using PRISM **Aim at 10^{-18}**

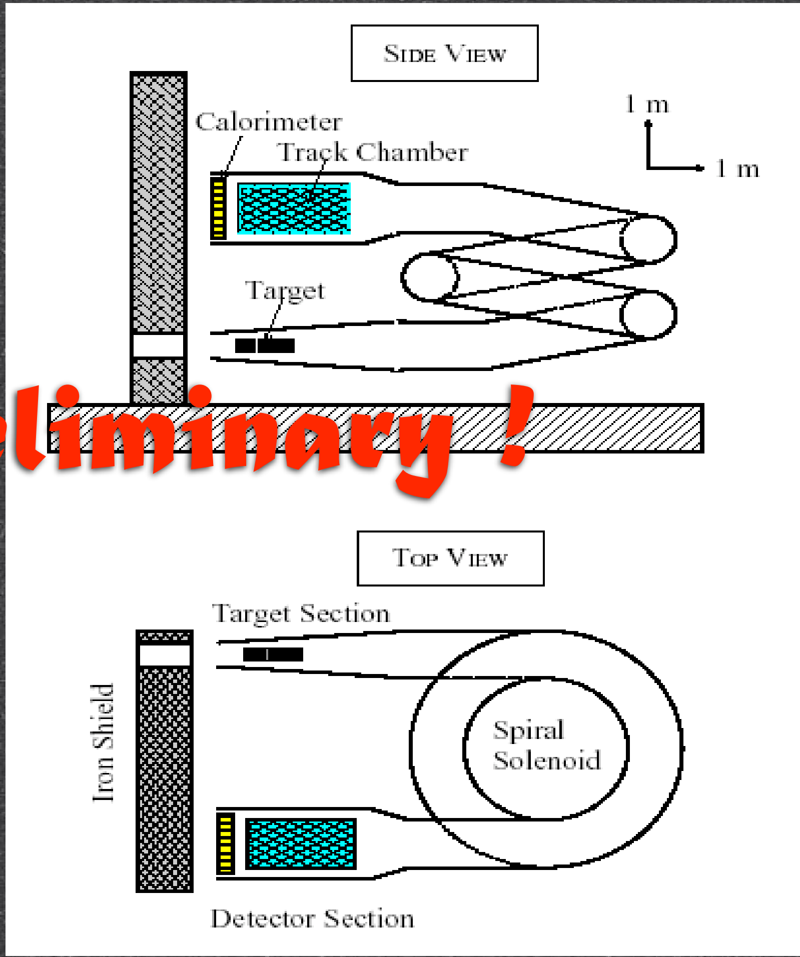
Detector Option:

Spiral solenoid spectrometer

eliminate low
energy particles
by a toroidal
magnetic field

$$D = \frac{1}{0.3B}\frac{s}{R}\frac{(p_s^2 + \frac{1}{2}p_t^2)}{p_s}$$

Preliminary !



BG Rejection Summary

- ***muon decay in orbit***
  - $(E_0\text{-}E)^5$
  - better e^+ momentum resolution
    - » a thin muon stopping target is helpful. (=several 100 g)
- ***radiative muon capture***
  - endpoint for Ti = 89.7MeV
    - » signal = 104.3 MeV
  - better e^+ momentum resolution
    - » a thin muon stopping target
- ***radiavtive π capture***
  - long flight length (150m)
    - » 30 m FFAG circumference x 5 turns
  - π surviving rate:
    10^{-18} at 68 MeV/c
- ***cosmic ray backgrounds***
  - 1kHz (duty factor: 1/1000)
- ***long transit time backgrounds***
  - FFAG timing (kicker)
- ***anti-proton***
  - absorber before FFAG
- ***beam electrons, electrons from muon decay in flight***
  - FFAG's momentum accpetance:
  - different β (out of time)
  - not bunched at FFAG ?

FFAG gives additional beam extinction between pulses.

PRIME Background Rates

Muon Decay in Orbit ($\propto (E_{\mu e} - E_e)^5$)
Detector Resolution $\Delta E_e = 235$ keV

Preliminary !

at the sensitivity of 10^{-18}

Background	Rate	comment
Muon decay in orbit	0.05	energy reso 350keV(FWHM)
Radiative muon capture	0.01	end point energy for Ti=89.7MeV
Radiative pion capture	0.03	long flight length in FFAG, 2 kicker
Pion decay in flight	0.008	long flight length in FFAG, 2 kicker
Beam electron	negligible	kinematically not allowed
Muon decay in flight	negligible	kinematically not allowed
Antiproton	negligible	absorber at FFAG entrance
Cosmic-ray	< 10^-7 events	low duty factor
Total	0.10	

New Spectrometer

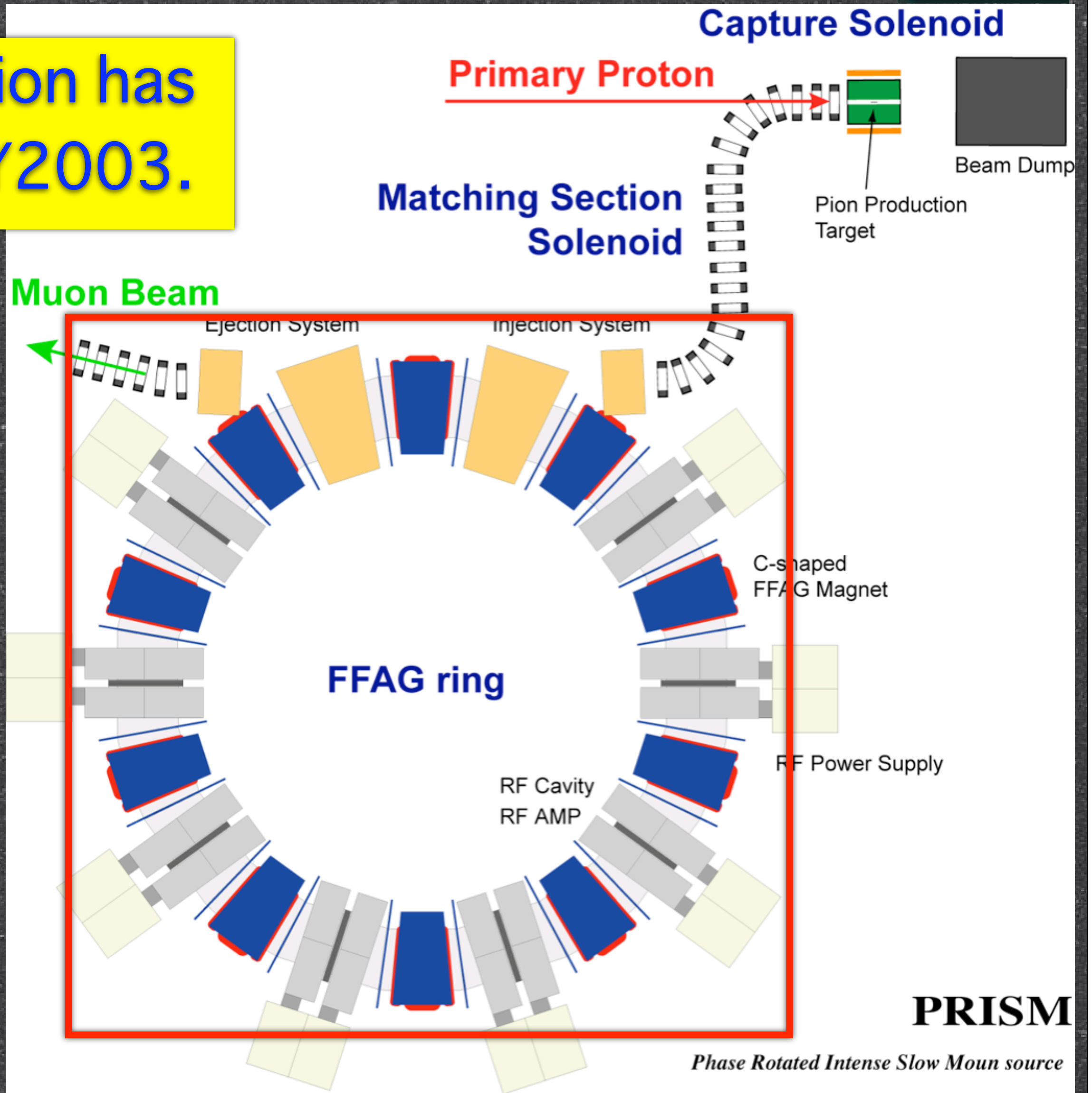
- A new spectrometer is under study.
- Rejection of low momentum particles from muon stopping target
  - curved solenoid
    - tracker does not see directly muon stopping target.
  - periodic solenoid (a la Bob Palmer)
  - emittance exchange (a la Bob Palmer)

PRISM-Ring R&D

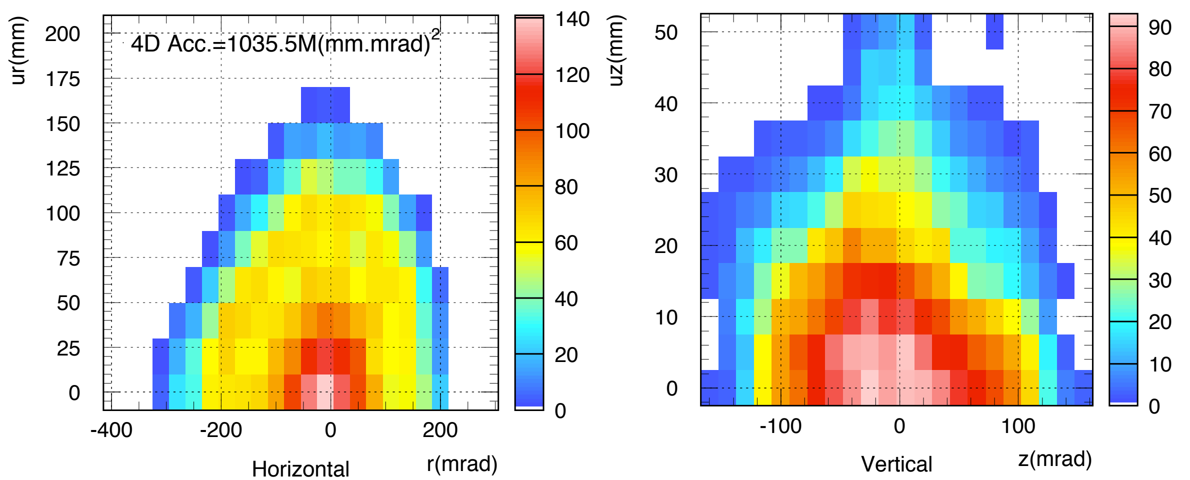
PRISM Ring Construction

PRISM ring construction has been approved in JFY2003.

- FFAG ring
- 5 year plan
  - construction at Osaka university
- Goals
  - proton/muon phase rotation
  - muon acceleration
  - muon cooling?

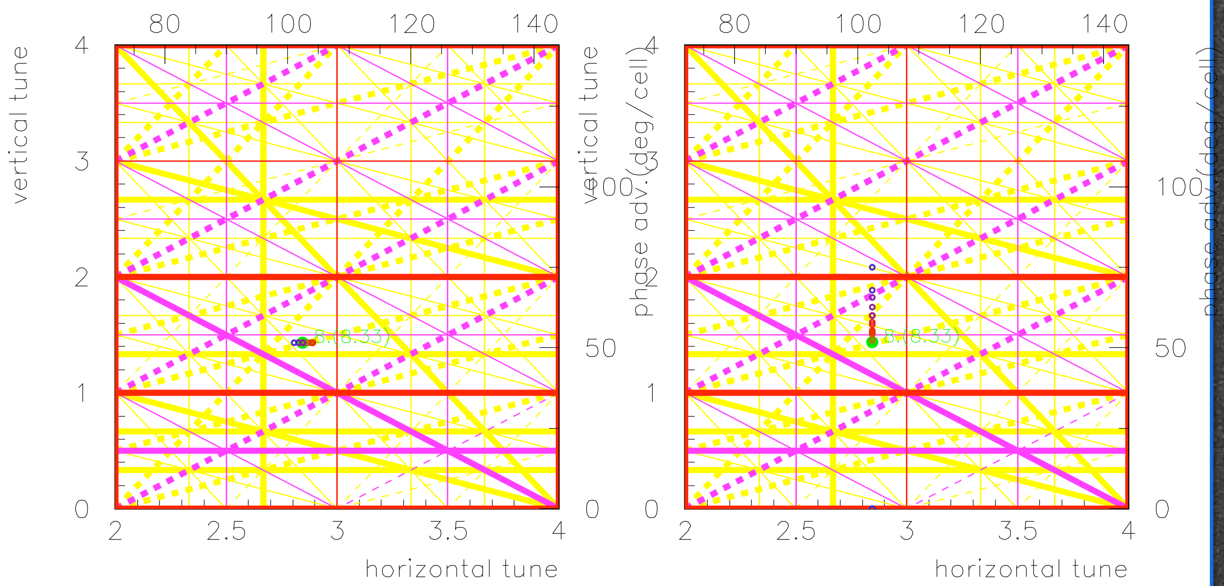


PRISM-FFAG Acceptance



Horizontal Acceptance
40000π mm mrad

Vertical Acceptance
6500π mm mrad

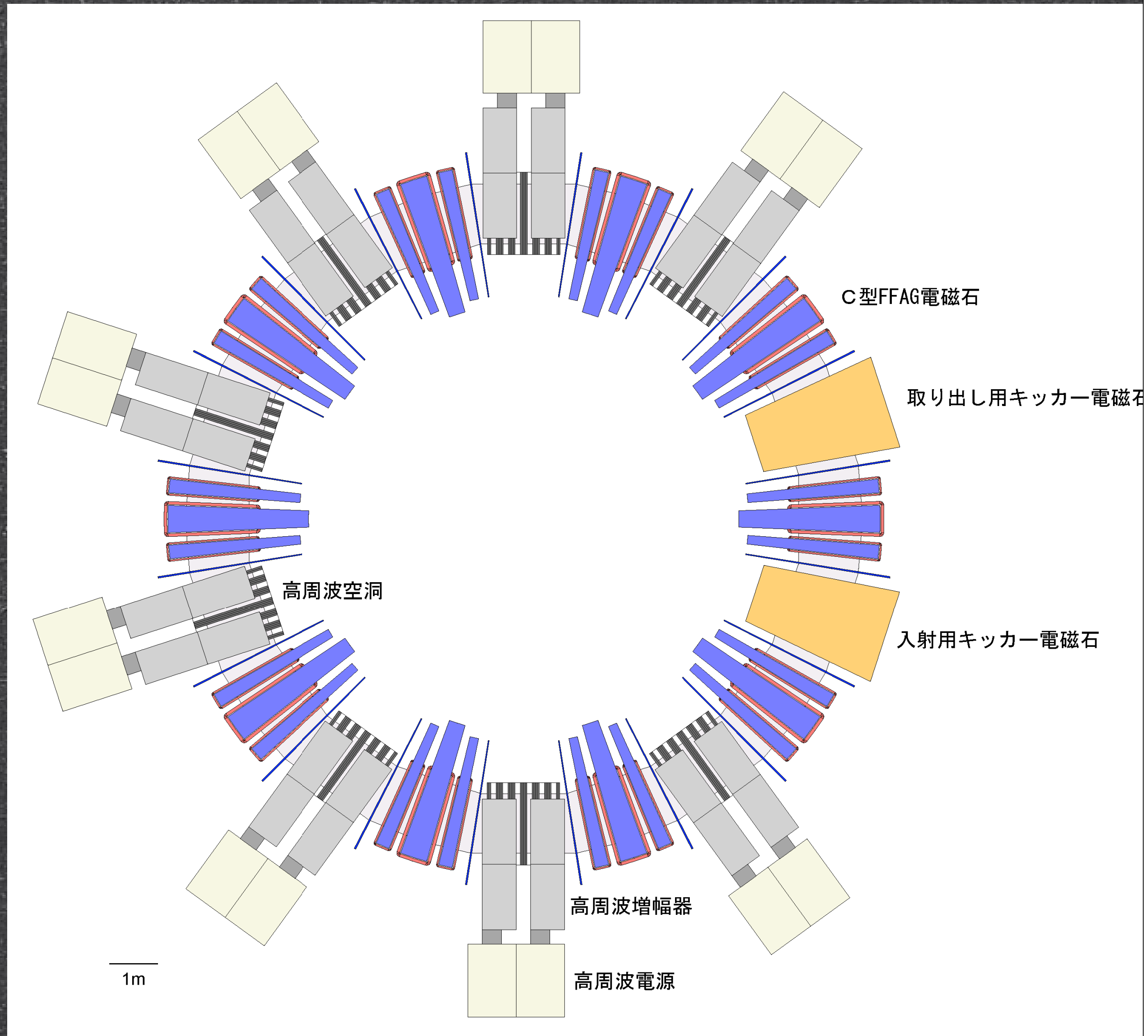


N=10
F/D=8
k=5
r0=6.5m
H:2.86
V:144

a la Akira
Sato (Osaka)

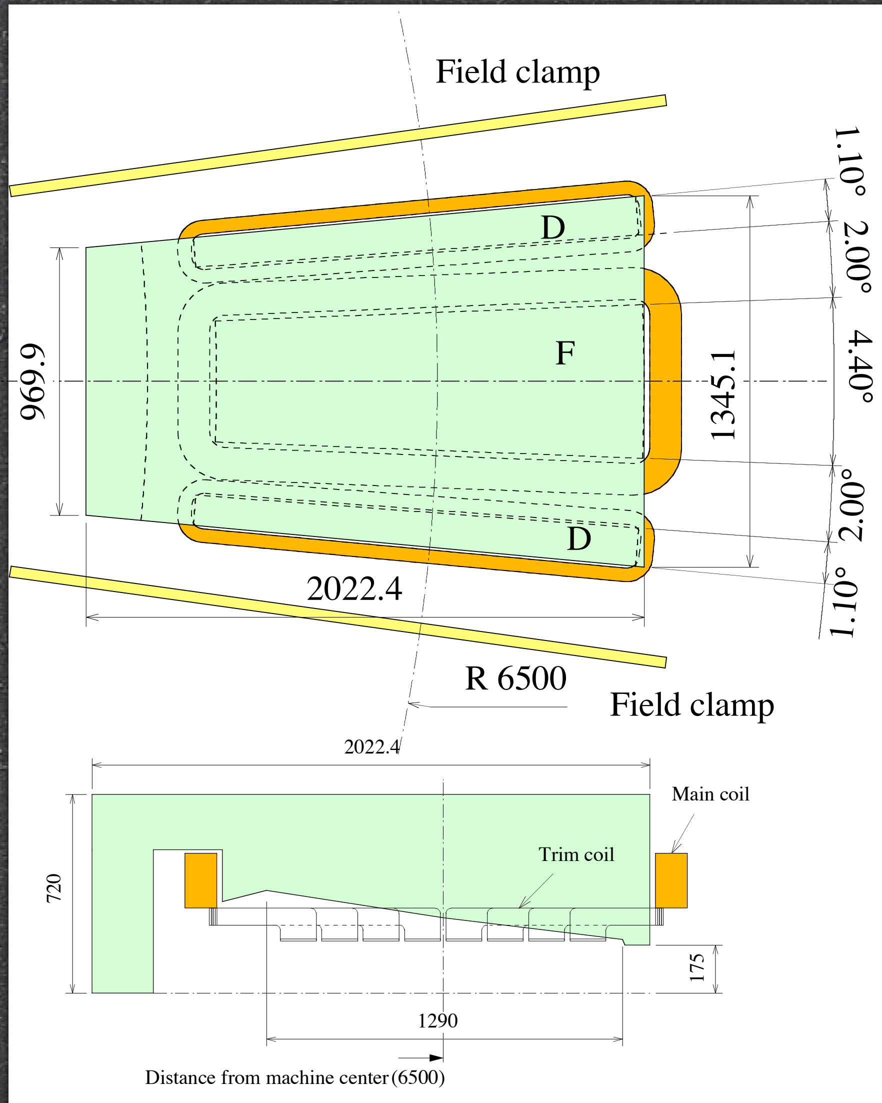
PRISM Lattice

- SCALING FFAG
- N=10
- k=5(4.6-5.2)
- F/D(BL)=8
- r0=6.5m for 68MeV/c
- half gap = 15cm
- mag. size 110cm @ F center
- Triplet
  - θ_F=4.40deg
  - θ_D=1.86deg
- tune
  - h : 2.86
  - v : 1.44
- acceptance
  - h : 40000 π mm mrad
  - v :   6500 π mm mrad



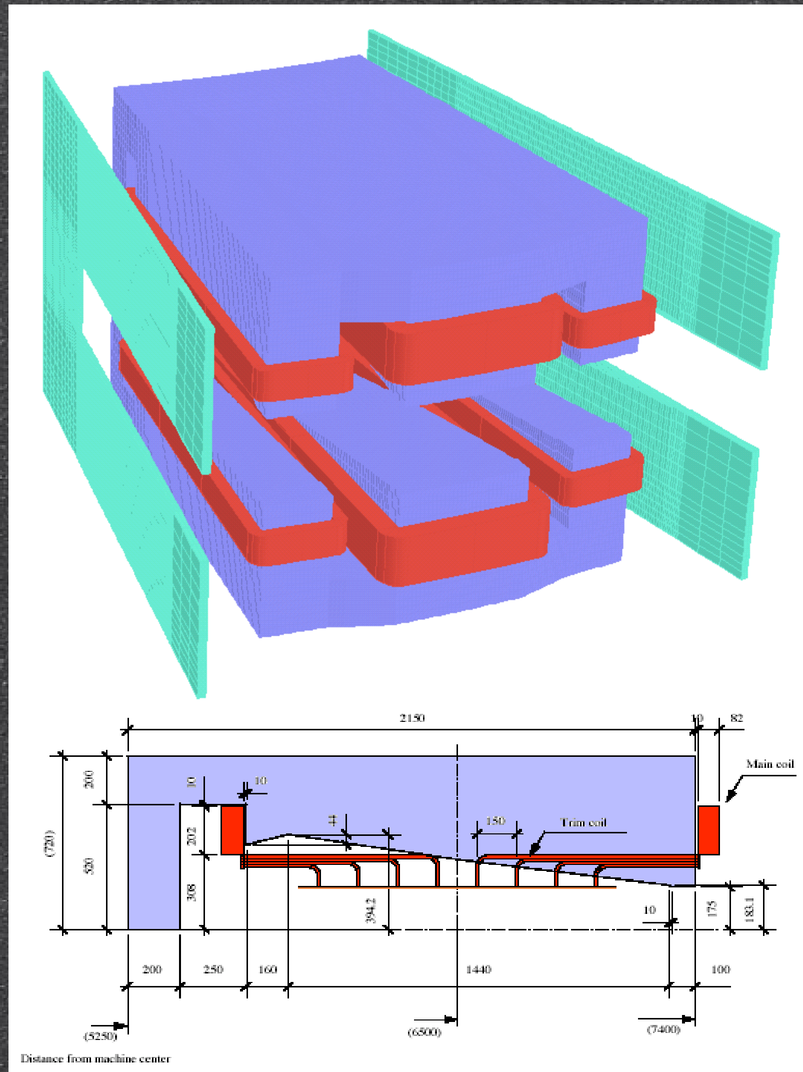
PRISM FFAG Magnet

- Radial Sector type
  - DFD Triplet
- Aperture
  - 100cm (H) and 30cm (V)
- Field gradient produced by pole shape
- Trim coil to adjust field gradient index.
- C-shape magnet



PRISM FFAG Magnets

- Design of the PRISM FFAG magnets has been made.
- Engineering studies have started.
- Biding will go out soon.
- The construction of the main magnet will take 2-3 years.



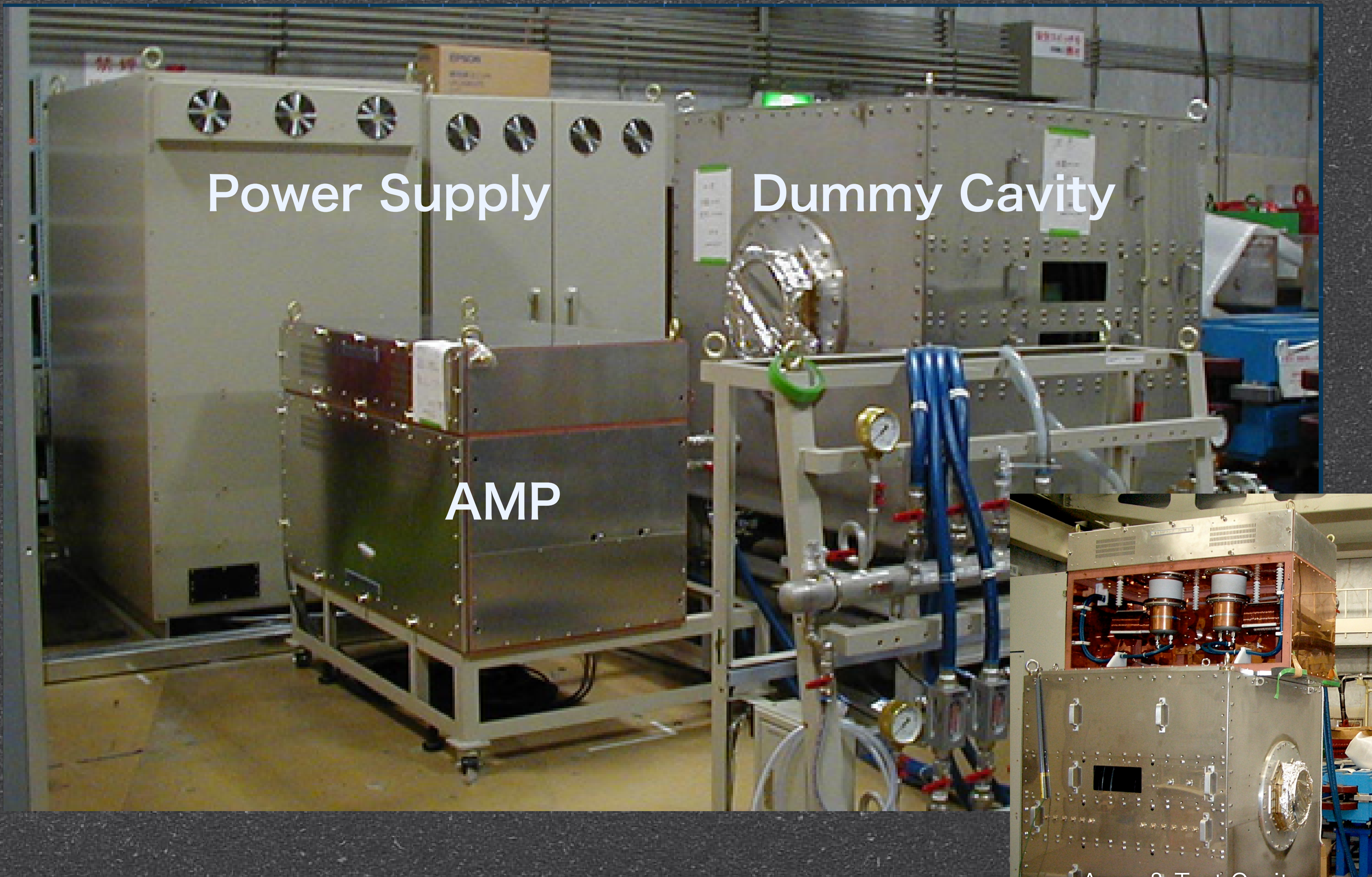
Coil Production (JFY'04)

D Coils : all 40 coils are completed.

F Coils : 6 out of 20 are completed.

D coil

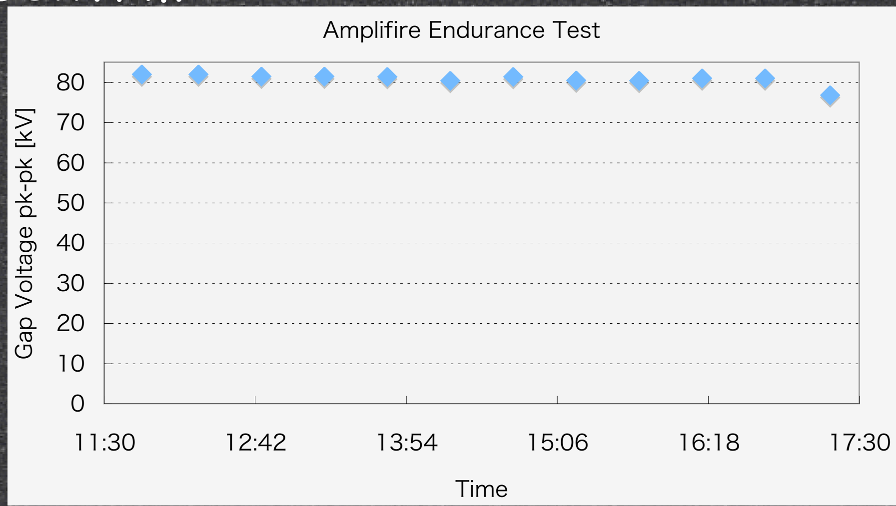
RF Amp. at RCNP, Osaka



Amp. & Test Cavity

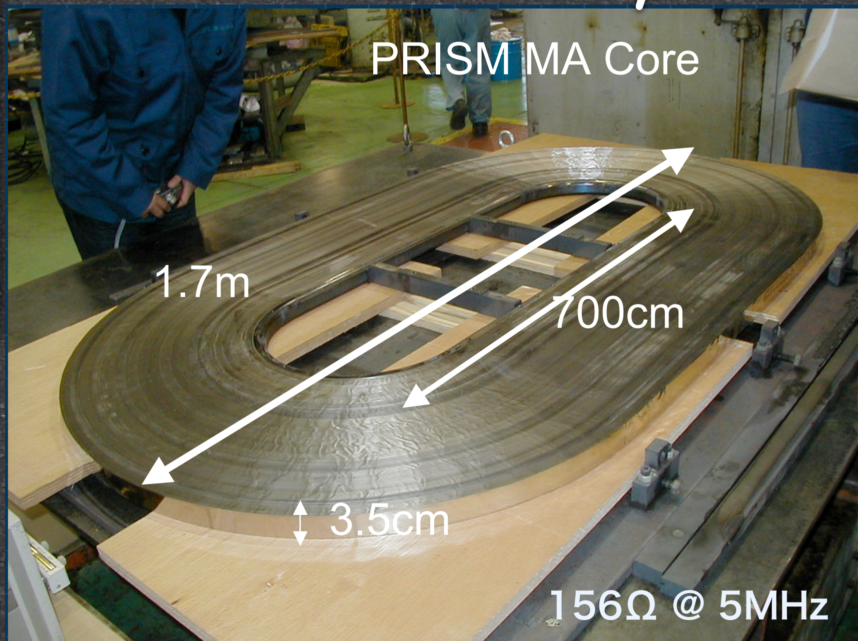
PRISM RF Amplifier Test

- Test Station of PRISM RF Sytem
  - RF Amplifier and Power supply
  - Test RF Cavity (1 gap、 700kΩ)
- Gap voltage of 86 kV p-p at 5 MHz achieved
  - correspond to about 150kV/m
- Long-term test
  - 100 Hz repetition
  - Burst length 30μsec
  - more than 6 hours



PRISM RF Cavity

rf cavity core



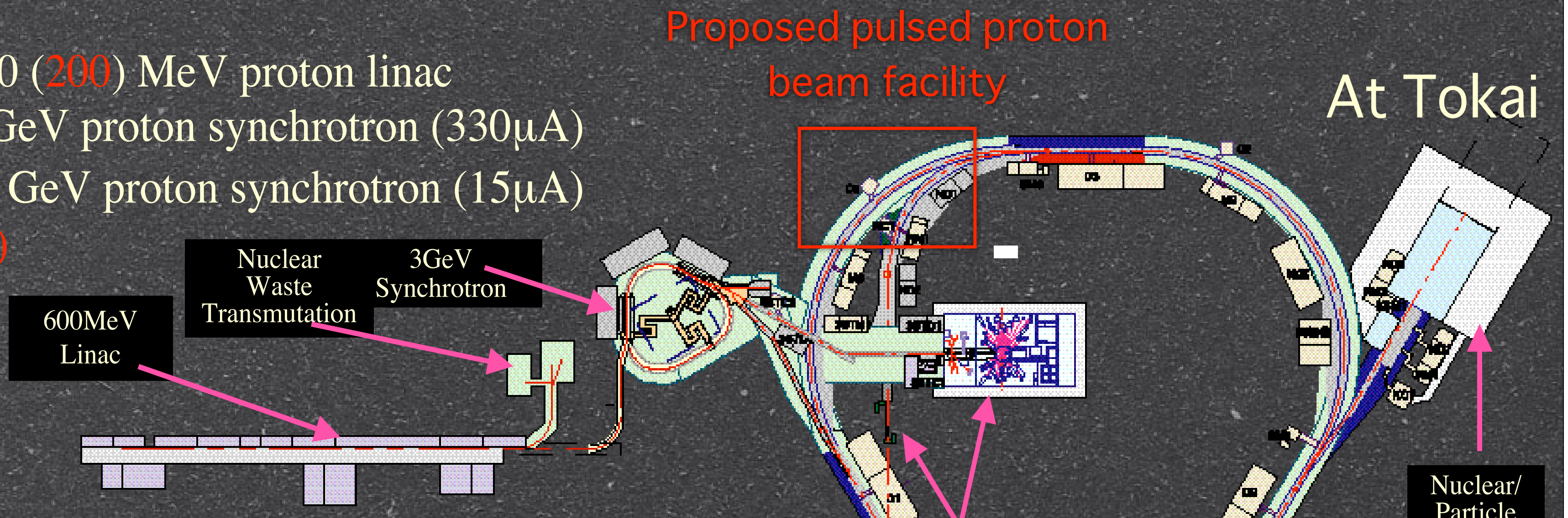
1 gap, Length 33cm,
6 MA cores, 2cm gap

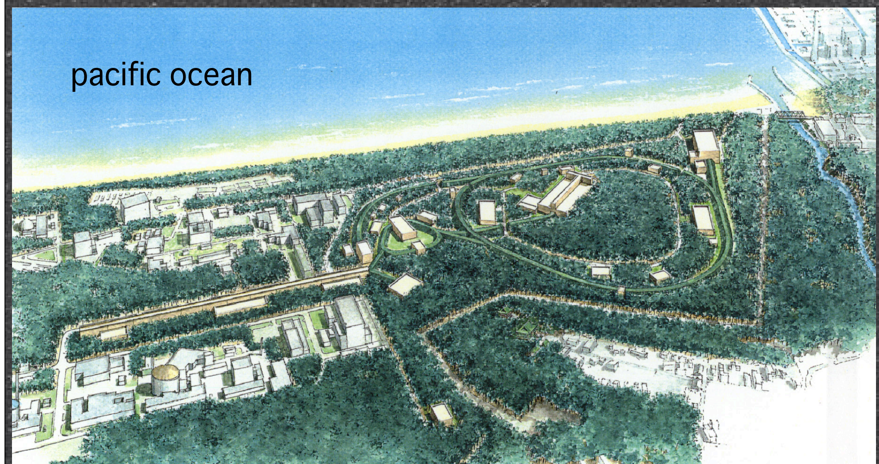
at J-PARC

J-PARC at Tokai

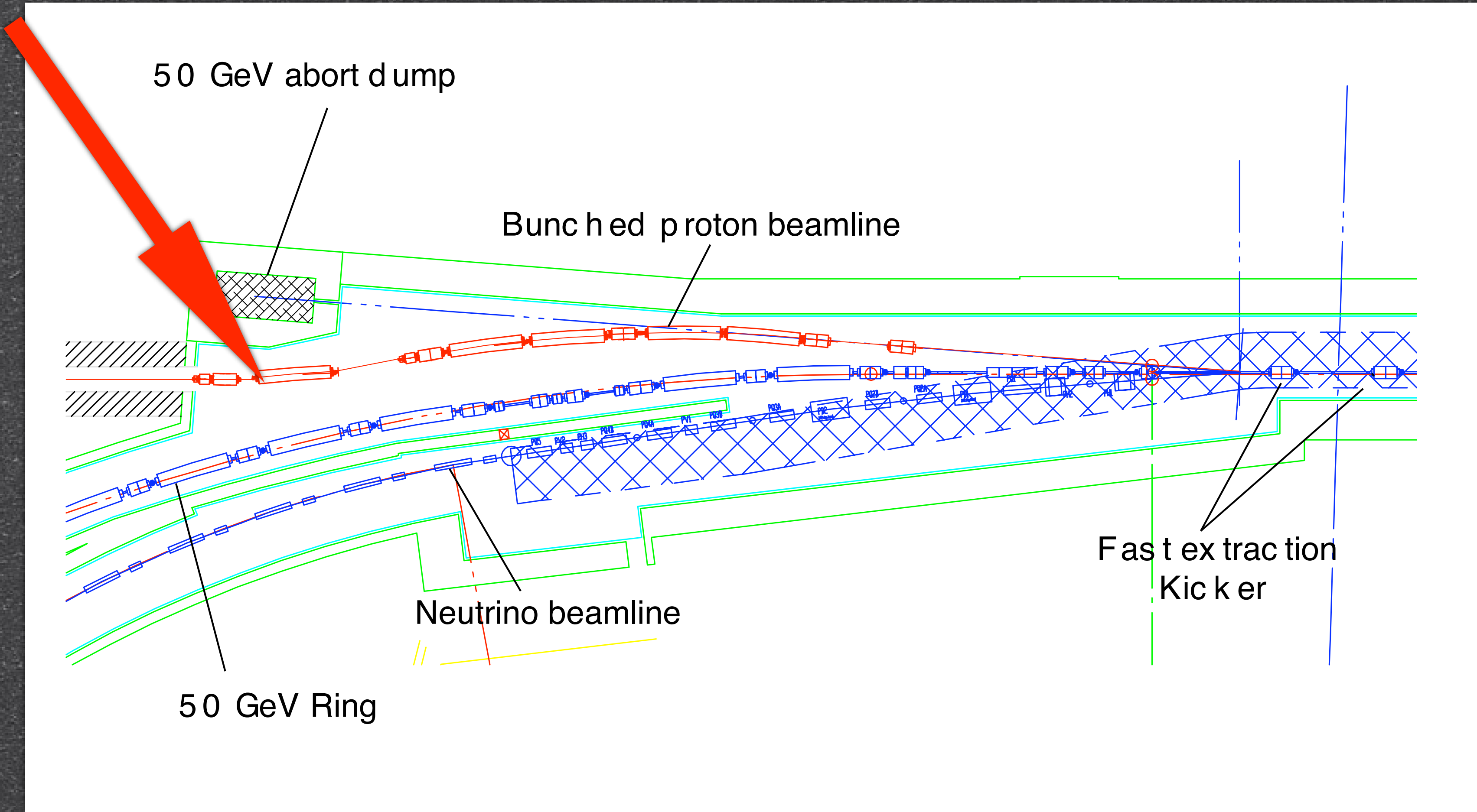
J-PARC = Japan Proton Accelerator Research Complex

400 (200) MeV proton linac
3 GeV proton synchrotron (330μA)
50 GeV proton synchrotron (15μA)
(40)





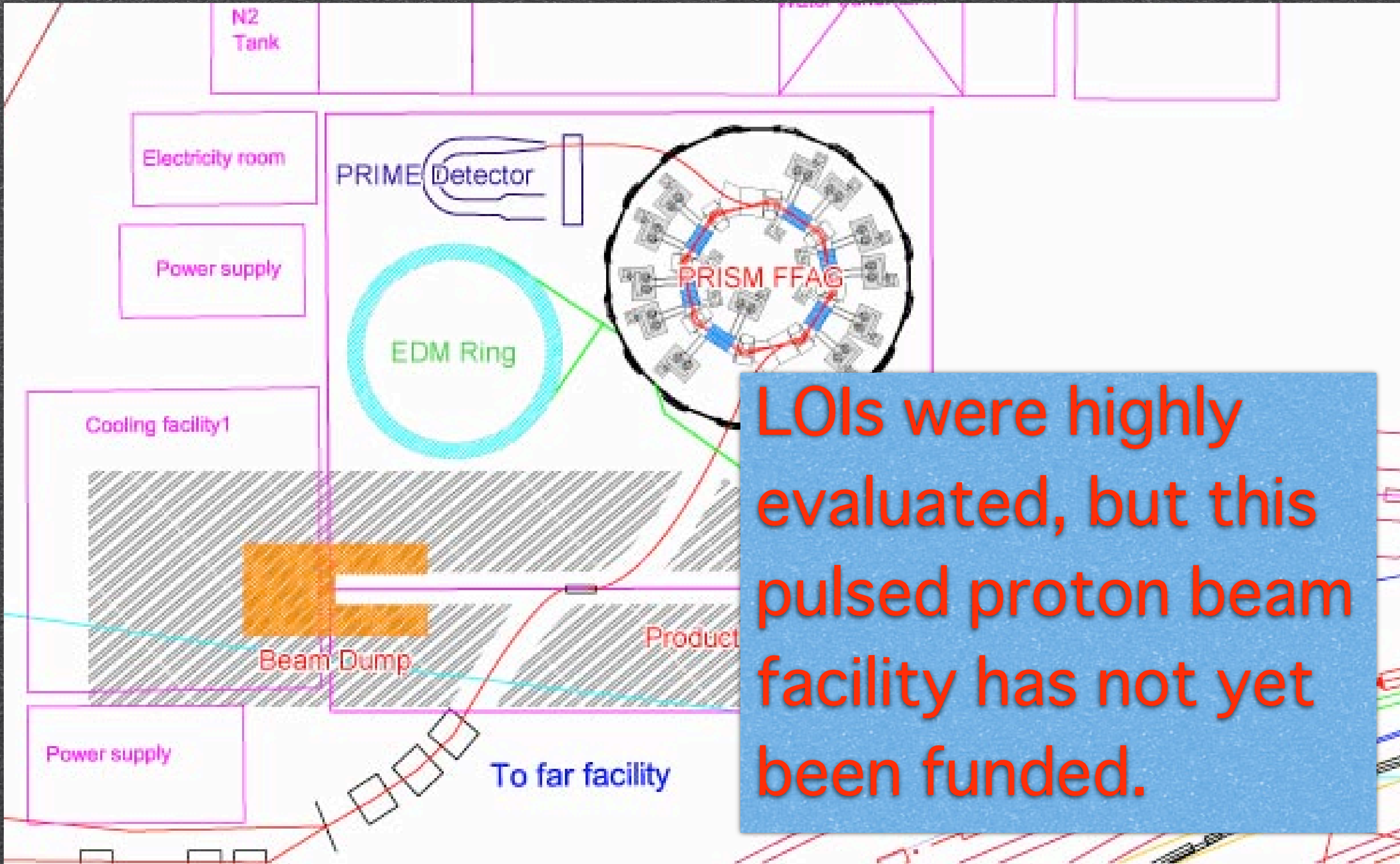
Proposed Fast Extraction



North-east side of the 50-GeV Ring

Muon Factory@J-PARC

Pulsed Proton Beam Facility is newly requested to J-PARC.



LOIs were highly evaluated, but this pulsed proton beam facility has not yet been funded.

PRISM Roadmap

PRISM Staging

Phase I

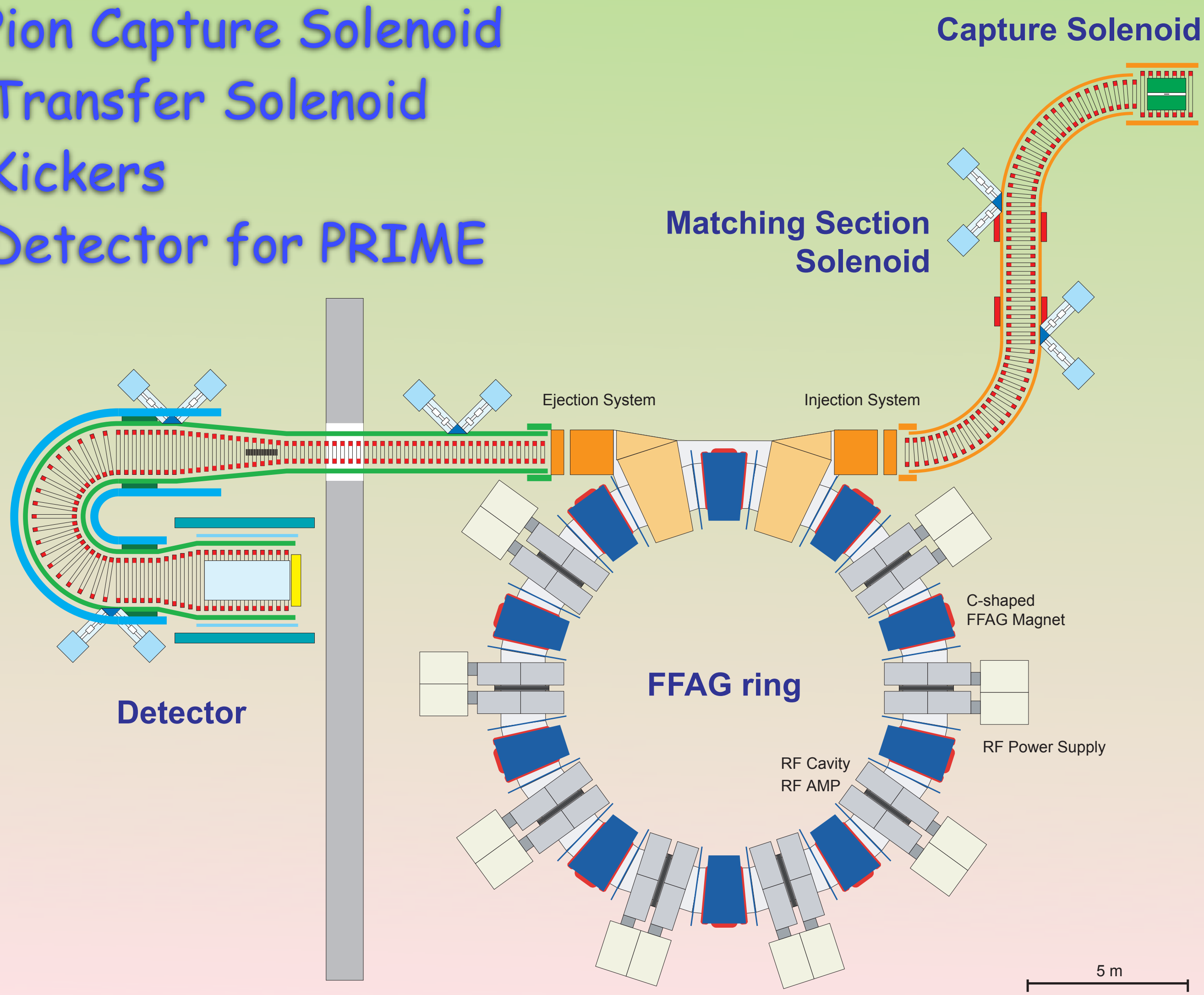
- Construct the Whole PRISM instumentations.
- Test the performance of PRISM.
- 2006-2009

Phase II

- Bring PRISM to high-intensity hadron machines.
- carry out the experiment (PRIME).
- after 2010

PRISM + PRIME

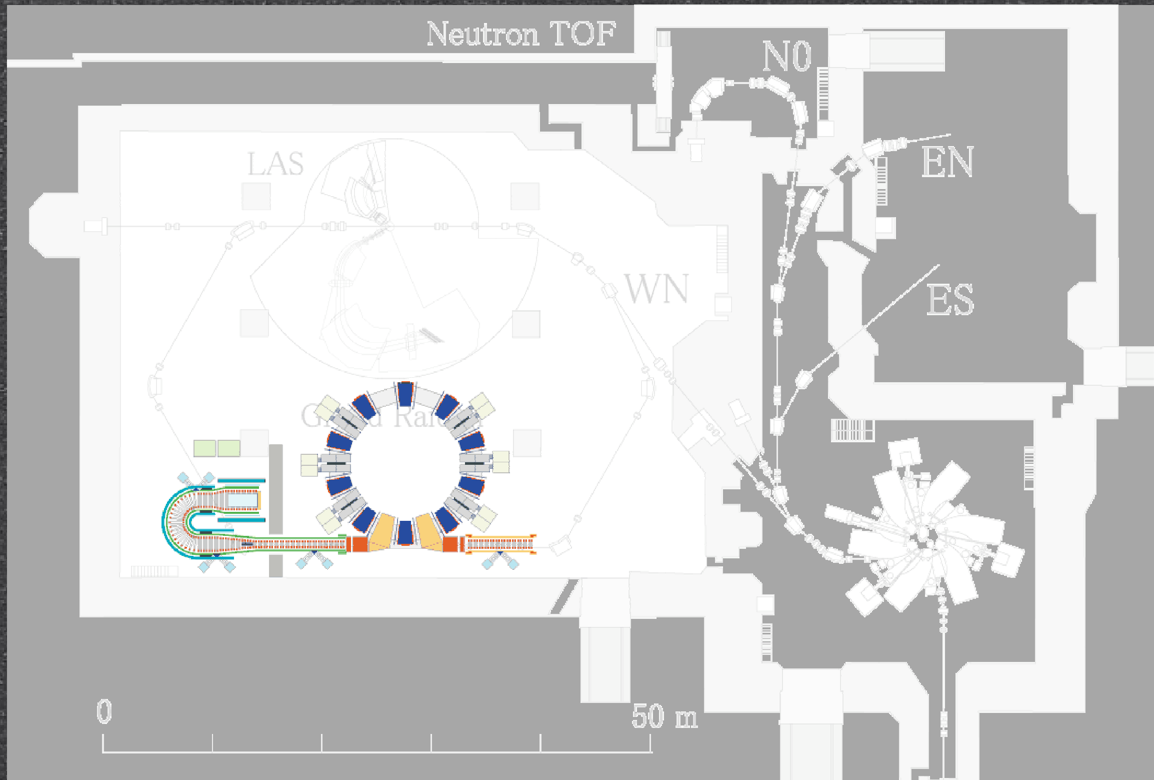
(1) Pion Capture Solenoid
(2) Transfer Solenoid
(3) Kickers
(4) Detector for PRIME



PRISM -Phase I @ RNCP

- Research Center for Nuclear Physics (RCNP), Osaka University
  - 400 MeV proton (above pion production threshold)
  - upto 5 micro A

Purpose : Test of fundamental performance of PRISM with muons.



Summary

- Search for lepton flavor violation in charged leptons, in particular in the muon, would provide great opportunity to find new physics beyond the Standard Model.
- The high-intensity, high-luminosity muon source, PRISM, is planned in Japan. The PRISM-FFAG ring is now under construction.
- Funding bids of the PRISM/Phase-I is now being prepared.
- International collaborators are looked for.

End of My Slides